Faculty of Agricultural Sciences

Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute)

University of Hohenheim

Agroecology in the Tropics and Subtropics

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Mitigate Habitat Degradation in the Semiarid Brazil – Potential and Limitation of the Endemic Tree *Spondias tuberosa* Arruda

Dissertation

Submitted in fulfillment of the requirements for the degree

doctor scientiarum agrarium (Dr. sc. agr.)

to the

Faculty of Agricultural Sciences

by

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Stuttgart, Germany, 2017

Date of defense of the doctoral thesis: Wednesday 8th November 2017

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Acho muita malvadeza

Tirar raiz de umbuzeiro

Pra fazer doce de corte

E se trocar por dinheiro

E prejudicar a planta

No período do sequeir[¥]

from Marialvo Barreto: “Se Umbuzeiro falasse...”

¥ Freely translated: *I think it is very evil – cutting the roots of the Umbuzeiro – just to make sweets – convert them to money – harming the plant – in the drought period.*

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Summary

Semiarid regions cover 15 % of the global land mass and are inhabited by approximately one billion people. Due to the strong rural character of these regions the well-being of 13 % of the world's population relying directly or indirectly on their ecosystem services. These ecosystem services are allocation of food and forage, purification of water, as well as pollination and seed dispersal, soil protection against desertification, and climate regulation. One of the most densely populated semiarid region is the Caatinga biome, that is located in the Brazilian Northeast. Its climate is hot semiarid (BSh) with little, erratic, and seasonal precipitation, ranging from 250 to 900 mm per year. The average annual temperatures range from 23°C to 27°C. An evapotranspiration above 2000 mm per year results in a negative water balance during 7 to 11 months. The deciduous natural Caatinga vegetation ranges from tropical dry forest to open shrubby vegetation, with a seasonal herbaceous layer.

Loss of its natural vegetation due to wood extraction, pasturing, and inappropriate land-use led to habitat degradation in up to 80 % of the area of the Caatinga biome. A degraded habitat jeopardizes the ecosystem services of the biome and poses a direct threat to its dwellers. In order to mitigate further habitat degradation an alternative land-use strategy is necessary to substitute or cut back prevailing land-use. The agro-industrial utilization of the fructiferous multipurpose tree *Spondias tuberosa* Arruda (Anacardiaceae), endemic to the Caatinga, has the potential to be a viable alternative to current irrigation farming and extensive animal husbandry. Its fruits, seed oil, and leaf extracts are especially attributed to economic and medical benefits.

The current utilization of *S. tuberosa* is limited to extractivism of its fruits that lacks sustainability and appears to be a finite resource. The natural population of *S. tuberosa* presents a weakening natural regeneration with a resultant over aged *S. tuberosa* population. Poor natural regeneration results from a multifactorial problem. Seed export by humans and domestic goats significantly reduce the share of *S. tuberosa* seeds in the Caatinga seed pool and the remaining seed rain is highly infested with the seed beetle *Amblycerus dispar* that destroys the embryo. At seedling stage, browsing goats reduce seedling survival of *S. tuberosa* significantly on disturbed Caatinga sites. Additionally, hunting activities of the Caatinga dwellers significantly reduced the abundance of natural dispersers, which facilitated long distance seed dispersal. Long distance seed dispersal, however, is an important mechanism for trees to answer to changing environmental conditions by tracking their ecological niche spatially in order to prevent extinction. At this juncture, *S. tuberosa* is not considered endangered based on the criteria of the International Union for Conservation of Nature, due to lacking information for a Red List of Threatened Species threat assessment. However, the combination of expected changing environmental conditions within the Caatinga and restricted natural regeneration of *S. tuberosa,* both discussed in literature, provides a strong evidence, that the *S. tuberosa* faces a high risk to become extinct.

To date, the area cropped with *S. tuberosa* is insignificant and a scientifically-backed cropping system is lacking. Constraining the scientifically-backed cropping system for *S. tuberosa* is its scientifically neglect, especially when compared with other Anacardiaceae, and the scientific interest is limited to the region of its occurrence. Problematic for plant physiological studies is the lack of genetically homogeneous plant material of the tree. Virtually, all available information about the response of *S. tuberosa* to abiotic stress or fertilization results from experiments with inhomogeneous plant material. Consequently, reported responses to treatments always contains a source of error due to the different feedbacks of different genotypes of this species. To date, the most homogeneous plant material available are grafted seedlings or seedlings originated from the same mother tree. *S. tuberosa* has not yet been subjected to cloning or breeding so far.

This work aims to provide a first basis for a scientifically-backed, extensive cropping system for *S. tuberosa* on disturbed Caatinga sites meliorated by the use of biochar, clay substrate, and goat manure. The effect of biochar, clay substrate, and goat manure with or without additional mineral fertilization as soil conditioner in planting holes were tested in a 23-months field experiment in a marginal Arenosol. Further, it was studied, whether changed soil physical conditions support establishment and development of one-year-old *S. tuberosa* seedlings. Besides soil physical parameters, the stem circumference growth, root architecture, stem and fine root biomass, root length density, root tuber fresh weight and volume, as well as survival rate of the seedlings were recorded.

At given application rates neither biochar nor clay substrate significantly affected soil physical parameters of the experimental soil. The application rate of 10 % v/v clay substrate, chosen from literature, seems to be too little to be affective on the experimental Arenosol, that was poor in fine particles (< 0.02 mm). The utilized biochar were proven hydrophobic and presumingly little porous duo to a low pyrolysis temperature. Both combined could explain the absence of a significant biochar-mediated change of soil physical parameters. Goat manure significantly increased total porosity, and significantly reduced soil bulk density. The water content at permanent wilting point, and volumetric water content within the planting holes during the experiment were significantly increased owing to melioration with goat manure. Due to a strong correlation ($R^2 = 0.75$) of water content at field capacity and water content at permanent wilting point, the available water capacity, an important target parameter for plant production, remained unchanged. Since a fast mineralization in the manure treatments was observed, loss of 93 % of the initial soil carbon stock occurred within the first 16 months of the experiment, the positive effect of goat manure application is likely not long-lasting.

Neither stem growth nor seedling survival was significantly affected by initial nutrient supplies or melioration. Conversely, fine root growth and root tuber growth were significantly affected by melioration. Goat manure in the planting holes led to significantly reduced fine root dry matter. Since fine root dry matter showed a weak but significant negative correlation with soil water content, the fine root reduction was evidently caused by increased soil water content resulting from goat manure application. The goat manure application also affected tuber growth significantly, and led to larger tubers. In contrast to the fine roots, root tuber growth did not respond to soil water content but showed a significant correlation with soil bulk density and total porosity. Reduced soil bulk density and increased soil porosity after goat manure addition application led to higher tuber volume.

The absence of treatment effects on stem growth and survival rate, as well as the negative growth response of the fine roots to increased soil water content of *S. tuberosa* seedlings, indicates that the available and utilized plant material is rather undomesticated and strongly adopted to its water and nutrient limited biome.

In order to proceed with the development of a cropping system for *S. tuberosa* and advance in *S. tuberosa* research, domestication and breeding should be in focus. It is necessary to get a reliable cultivar with a stable yield with a shortened time between germination and first fruit set as well as genetically homogeneous plant material. Otherwise fundamental research on

S. tuberosa will continue to contain a bias due to different feedbacks of different genotypes. Furthermore, the postulated agro-industrial potential of *S. tuberosa* cannot provide an alternative land-use strategy to help mitigate further habitat degradation within the Caatinga when there is no reliable and short-term monetary benefit for the Caatinga dweller.

Zusammenfassung

Semiaride Regionen bedecken rund 15 % der Erdoberfläche und werden von circa einer Milliarde Menschen bewohnt. Aufgrund des starken landwirtschaftlichen Charakters dieser Regionen ist das Wohlergehen von etwa 13 % der Weltbevölkerung direkt oder indirekt von ihren Ökosystemdienstleistungen abhängig. Diese Ökosystemdienstleistungen sind unter anderem Bereitstellung von Nahrungs- und Futtermitteln, Reinigung von Süßwasser sowie Bestäubung, Samenverbreitung, Schutz der Böden vor Verwüstung und Regulierung des Klimas. Einer der am dichtesten besiedelten semiariden Regionen ist das Caatinga Biom, welches sich im Nordosten Brasiliens befindet. Das Klima der Caatinga ist heiß semiarid (BSh) mit geringem, unbeständigem, saisonalem Niederschlag, zwischen 250 und 900 mm pro Jahr. Die Jahresmitteltemperatur reicht von 23°C bis 27°C und die jährliche Evapotranspiration ist mit über 2000 mm hoch. Daraus resultiert eine negative Wasserbilanz während 7 bis 11 Monaten in der Caatinga. Die natürliche, sommergrüne Vegetation der Caatinga reicht von einer offenen Buschlandschaft bis zu einem tropischen Trockenwald mit einer saisonalen Krautschicht. Der Verlust dieser natürlichen Vegetation gefördert durch Holzeinschlag, Beweidung und unangemessene Feldwirtschaft führt bis heute zu einem gestörten natürlichen Lebensraum auf 80 % der Fläche der Caatinga. Der gestörte natürliche Lebensraum wiederum beeinträchtigt Ökosystemdienstleistungen des Bioms, was eine direkte Bedrohung für dessen Bewohner darstellt. Um eine weitere Schädigung des natürlichen Lebensraums abzuschwächen ist eine alternative Landnutzung zwingend. Die agrarindustrielle Nutzung des endemischen, fruchttragenden Mehrzweckbaums *Spondias tuberosa* Arruda (Anacardiaceae) hat das Potenzial eine tragfähige Alternative zur gegenwärtigen Bewässerungslandwirtschaft und extensiven Viehhaltung innerhalb der Caatinga zu sein. Besonders seine Früchte, das Samenöl und die Blattextrakte werden mit großem ökonomischen und medizinischen Nutzen assoziiert.

Bis dato beschränkt sich die Nutzung von *S. tuberosa* auf das Sammeln der Früchte von natürlich vorkommenden Individuen. Dieser Nutzung fehlt die Nachhaltigkeit und die Ressource

erscheint endlich zu sein. Denn die natürliche Population von *S. tuberosa* leidet unter einer geschwächten natürlichen Regeneration was zu einer überalterten Population geführt hat. Die geschwächte natürliche Regeneration scheint aus einer multifaktoriellen Störung zu resultieren: Der Export von *S. tuberosa* Samen durch den Menschen und die Hausziege reduziert signifikant den Anteil dieser im Samenpool der Caatinga. Die in der Caatinga verbleibenden Samen leiden fast ausnahmslos unter dem Befall des Samenkäfers *Amblycerus dispar*, der die Embryonen der Samen zerstört. Weiterhin wird auf gestörten Caatinga Flächen die Überlebensrate von *S. tuberosa* Jungpflanzen signifikant durch weidende Ziegen reduziert. Letztlich ist die Verbreitung der *S. tuberosa* Samen über weite Strecken gestört, da das Vorkommen der natürlichen Verbreiter durch Bejagung stark zurückgegangen ist. Die Verbreitung von Samen über weite Strecken ist aber besonders wichtig für den Baum, da es ihm ermöglicht so seiner ökologischen Nische räumlich zu folgen und sich damit an sich ändernde Umweltbedingungen anzupassen. Nach den Kriterien der Internationalen Union zur Bewahrung der Natur und natürlicher Ressourcen ist *S. tuberosa* zum jetzigen Zeitpunkt nicht als gefährdet eingestuft, da für eine Kategorisierung des Baumes für die Rote Liste gefährdeter Arten jegliche Datengrundlage fehlt. Wenn man aber die in der wissenschaftlichen Literatur aufgezeigte zu erwartende Klimaänderung innerhalb der Caatinga und die eingeschränkte natürliche Regeneration von *S. tuberosa* berücksichtigt, erhärtet sich der Verdacht, dass *S. tuberosa* einem hohen Risiko ausgesetzt ist auszusterben.

Bislang ist die Fläche auf der *S. tuberosa* kultiviert wird unwesentlich und eine auf wissenschaftlichen Erkenntnissen basierende Anbaumethode existiert nicht. Problematisch für die Entwicklung einer wissenschaftlich gestützten Anbaumethode ist die Tatsache, dass *S. tuberosa* im Vergleich zu anderen ökonomisch relevanten Arten aus der Familie der Anacardiaceae wissenschaftlich vernachlässigt ist. Das wissenschaftliche Interesse an diesem Baum ist stark regional und beschränkt sich auf die Region seines Vorkommens. Die Aussagekraft von Studien über die Physiologie von *S. tuberosa* wird durch das Fehlen von genetisch homogenem Pflanzenmaterial beeinträchtigt. Bis dato gewonnene Erkenntnisse und verfügbare Informationen über die Reaktion von *S. tuberosa* auf abiotischen Stress oder Düngung resultiert aus Experimenten, die mit inhomogenem Pflanzenmaterial durchgeführt wurden. Folglich beinhalten jegliche Antworten von *S. tuberosa* auf verschiedene Behandlungen stets eine Fehlerquelle aufgrund verschiedener Feedbacks der unterschiedlichen Genotypen dieser Art. Für *S. tuberosa* existiert noch keine Züchtung und aufgepfropfte Setzlinge oder Setzlinge deren Samen von dem selben Mutterbaum stammen sind das am homogensten verfügbare Pflanzenmaterial.

Die vorliegende Arbeit leistet einen Beitrag hin zur Entwicklung eines mehr wissenschaftlich fundierten extensiven Anbausystems für *S. tuberosa*. Ein Anbausystem, angepasst an gestörte Caatinga Flächen, das die Melioration dieser Flächen mittels Biokohle, Tonsubstrat und Ziegenmist einschließt. Der Wirksamkeit von Biokohle, Tonsubstrat und Ziegenmist als Zuschlagsstoffe für Pflanzlöcher, mit oder ohne Mineraldünger, wurde während einem 23-monatigen Feldversuch auf einem marginalen Arenosol Standort untersucht. Darüber hinaus wurde untersucht, ob die veränderten bodenphysikalischen Eigenschaften das Wachstum und die Entwicklung von *S. tuberosa* Setzlingen unterstützt. Neben bodenphysikalischen Parametern wurde im Feldversuch der Stammumfang, die Wurzelarchitektur, Stamm- und Feinwurzelbiomasse, Wurzellängendichte, Wurzelknollengröße und -frischgewicht, sowie die Überlebensrate der Setzlinge erfasst.

Weder Biokohle noch Tonsubstrat zeigten bei gegebener Aufwandmenge einen signifikanten Effekt auf die bodenphysikalischen Parameter des Versuchsbodens. Die in der Literatur für Tonsubstrat empfohlene Aufwandmenge von 10 % v/v erscheint zu gering, um die bodenphysikalischen Parameter des Arenosol des Feldversuchs zu beeinflussen, der sehr arm an feinen Bodenpartikeln (< 0,02 mm) ist. Bei der verwendeten Biokohle wurde Hydrophobizität nachgewiesen und aufgrund einer niedrigen Pyrolysetemperatur weist die Kohle vermutlich eine geringe Porosität auf. Diese beiden Merkmale können der Grund dafür sein, dass keine biokohlebedingte Veränderung der bodenphysikalischen Parameter beobachtet wurde. Ziegenmist erhöhte signifikant die Porosität des Versuchsbodens und reduzierte signifikant dessen Trockenrohdichten. Der Wassergehalt am permanenten Welkepunkt und der volumetrische Wassergehalt in den Pflanzlöchern wurden durch den Ziegenmist signifikant erhöht. Aufgrund einer starken Korrelation ($R^2 = 0,75$) von Feldkapazität und Wassergehalt am permanenten Welkepunkt blieb die für die Pflanzenproduktion wichtige Maßzahl, die nutzbare Feldkapazität, unverändert. Unter den gegebenen Bedingungen wurde eine sehr starke Mineralisierung der organischen Substanz in der Mistbehandlung beobachtet, 93 % des anfänglichen Kohlenstoffgehalts war nach den ersten 16 Monaten des Versuchs nicht mehr vorhanden. Aufgrund dessen ist anzunehmen, dass der positive Effekt der einmaligen Anwendung von Ziegenmist auf den Boden nicht von Dauer ist.

Weder das Stammwachstum noch das Überleben der Setzlinge wurde signifikant von der anfänglichen Nährstoffversorgung oder der Melioration beeinflusst, wohingegen die Melioration das Wachstum der Feinwurzeln und das der Wurzelknollen signifikant beeinflusste. Der Ziegenmist in den Pflanzlöchern führte zu signifikant geringerer Feinwurzel-Trockenmasse und die Feinwurzel-Trockenmasse korrelierte schwach aber signifikant mit dem Wassergehalt in den Pflanzlöchern. Der negative Effekt des Ziegenmists auf die Feinwurzel-Trockenmasse resultiert demnach aus dem erhöhten volumetrischen Wassergehalt in den Pflanzlöchern. Die Anwendung von Ziegenmist hatte auch auf das Wurzelknollenwachstum einen signifikanten Effekt und führte zu größeren Knollen. Im Gegensatz zu den Feinwurzeln reagierten die Wurzelknollen nicht auf den erhöhten Wassergehalt im Pflanzloch, aber auf Porosität und Trockenrohdichten. Reduzierte Trockenrohdichte und erhöhte Porosität des Bodens behandelt mit Ziegenmist führte zu größerem Knollenvolumen.

Die Abwesenheit von Behandlungseffekten auf das Stammwachstum und die Überlebensrate *S. tuberosa* Setzling, sowie der negative Effekt des erhöhten Wassergehalts des Bodens auf das Feinwurzelwachstum von *S. tuberosa* ist ein Hinweis darauf, dass das verfügbare und verwendete Pflanzenmaterial eher Wildpflanzen waren. Denn Wildpflanzen aus wasser- und nährstofflimitierten Biomen, so wie *S. tuberosa*, zeigen ein langsames Wachstum auf, das sich durch Nähstoff- bzw. Wasserzugabe nicht positiv ändert.

Um weitere Fortschritte in der Entwicklung einer Anbaumethode zu erzielen, sollte die Domestizierung von *S. tuberosa* und gezielte züchterische Maßnahmen im Fokus stehen. Das dadurch gewonnene genetisch homogene Pflanzenmaterial schafft erst die Voraussetzung für die postulierte agrarindustrielle Nutzung von *S. tuberosa* in einer alternativen Landnutzungsstrategie.

Resumo

A região semiárida cobre 15 % da superfície terrestre do globo e é habitada por aproximadamente 1 bilhão de pessoas. Devido à forte característica rural dessa regão, o bem-estar de 13 % da população mundial depende, direta ou indiretamente, dos serviços ambientais. Entre os serviços ambientais oferecidos estão a provisão de alimento, forragem, água, polinização e dispersão de sementes, proteção do solo contra desertificação e regulação do clima. Uma das regiões semiáridas mais densamente populadas é o bioma Caatinga, localizado no nordeste Brasileiro. Seu clima é semiárido quente (BSh) com precipitação escassa, irregular e sazonal, entre 250 e 900 mm por ano. A temperatura média anual varia entre 23°C e 27°C e conta com evapotranspiração acima 2000 mm por ano o que resulta em um balanço negativo da água durante 7 a 11 meses. A vegetação decídua, natural da Caatinga, varia entre floresta tropical seca a arbustiva aberta, com um estrato herbáceo sazonal.

A perda da vegetação natural devido a extração de madeira, pastagem e uso inapropriado das terras levou a degradação em até 80 % do bioma Caatinga. Um habitat degradado fragiliza os serviços ambientais do bioma e ameaça diretamente seus habitantes. No intuito de diminuir o impacto ambiental é necessário desenvolver uma estratégia alternativa de uso das terras para substituir ou eliminar o modo predominante. O uso agroindustrial da árvore frutífera polivalente *Spondias tuberosa* Arruda (Anacardiaceae), endêmica da Caatinga, tem o potencial de ser uma alternativa viável para a atual agricultura irrigada e pecuária extensiva. Benefícios econômicos e medicinais são atribuídos a suas frutas, óleo da semente e extrato das folhas. O uso atual de *S. tuberosa* está limitado ao extrativismo de suas frutas de forma insustentável e aparenta ser um recurso finito. A população natural de *S. tuberosa* apresenta uma debilidade natural de regeneração o que leva a uma população envelhecida. Uma regeneração natural débil resulta em um problema multifatorial. A dispersão de sementes por humanos e caprinos reduz significativamente a cota das mesmas no banco de sementes da Caatinga e a chuva de semente apresenta altos níveis de infestamento do besouro *Amblycerus dispar* que destrói o embrião. No estágio de muda, o pastoreio de caprinos diminui a sobrevivência de *S. tuberosa* em áreas degradadas da Caatinga. Ademais, a caça realizada pelo moradores da região reduz substancialmente a quantidade de dispersores naturais, que facilitariam o transporte das sementes em longa distância. A dispersão de longa distância é um importante mecanismo das árvores para responder a mudanças ambientais pois, através dela, é possível acompanhar o nicho espacial ecológico e assim prevenir sua extinção. Nesse contexto, *S. tuberosa* não pode ser considerada em perigo com base nos critérios da União Internacional para a Conservação da Natureza e Recursos Naturais (IUCN), devido à falta de informação na Lista Vermelha de Espécies Ameaçadas. Entretanto, a combinação de uma mudança, já esperada, das condições ambientais da Caatinga e restrições naturais na regeneração de *S. tuberosa*, ambos já discutidos na literatura, fornece uma forte evidência que *S. tuberosa* enfrenta um alto risco de tornar-se extinta.

Atualmente, a área coberta por *S. tuberosa* é insignificante e falta um sistema de manejo com base científica, o que confirma a negligência em que se encontra essa espécie, especialmente se comparada a outras Anacardiaceae. Além disso, o interesse científico é limitado à região em que ocorre. A falta de material geneticamente homogênico da árvore cria uma barreira para estudos fisiológicos. Praticamente, toda informação disponível sobre a resposta de *S. tuberosa* ao estresse abiótico ou fertilização resulta de experimentos com materiais não-homogênicos. Como consequência, as respostas encontradas a tratamentos sempre contêm fontes de erro devido a distintos feedbacks de diferentes genótipos da espécie. Hoje, o material mais homogênico disponível são os enxertos de muda ou mudas originadas de uma mesma árvore mãe. *S. tuberosa* que ainda não passou por processos como clonagem ou cultivo.

Este trabalho tem como objetivo promover uma primeira base para um sistema de manejo extensivo de fundamento cientifico para *S. tuberosa* em áreas degradadas da Caatinga melhorada pelo uso de biocarvão, substrato de argila e esterco de caprinos. Foram testados os efeitos do biocarvão, substrato de argila e esterco de caprino, com ou sem adição de fertilizante mineral como condicionante de solo, em um experimento de campo com duração de 23 meses em Neosolo Quartzarênico empobrecido. Ademais, estudou-se o melhoramento das condições físicas do solo suportam o estabelecimento e desenvolvimento de mudas de um ano de *S. tuberosa*. Além dos parâmetros físicos do solo, foram observados o crescimento da circunferência do caule, a arquitetura da raiz, a biomassa das raízes finas, o comprimento das raízes, o peso fresco e volume do tubérculo da raiz e a taxa de sobrevivência das mudas.

De acordo com os parâmetros usados, com doses de aplicação determinadas, nem o biocarvão nem o substrato de argila afetaram significativamente os parâmetros físicos do solo. O padrão de aplicação de 10 % v/v substrato de argila, escolhido com base na literatura, parece ser muito pouco para produzir efeito no Neosolo Quartzarênico, que é pobre em partículas finas (< 0.02 mm). O biocarvão utilizado se mostrou hidrofóbico e assim pouco poroso devido a baixa temperatura de pirólise. Essa combinação de fatores poderia explicar a falta de mudança significativa mediada pelo biocarvão nos parâmetros físicos do solo. O esterco de caprino aumentou de forma considerável a porosidade total e reduziu substancialmente a densidade do solo. A adição de esterco de caprinos provocou um aumento notável da umidade no ponto de murcha e a quantidade de água nas covas de plantio durante todo o experimento. Devido a forte correlação (R^2 = 0,75) entre a absorção da água e os ponto de murcha e capacidade do campo, a capacidade da água disponível, que representa um importante parâmetro na produção de plantas, permaneceu a mesma. Entretanto, como foi observada uma aceleração na mineralização nos locais tratados com esterco, com perda de 93 % no estoque inicial de carbono durante os 16 meses do experimento, é provável que o efeito positivo do uso do mesmo não dure muito.

A sobrevivência das mudas e o crescimento dos caules não foram afetados de forma significativa pela adição de nutrientes ou pela melhoria do solo. Por outro lado, o melhoramento do solo afetou substancialmente o crescimento das raízes finas e do tubérculo. O uso de esterco de caprinos nas covas de plantio levou a uma acentuada redução da matéria seca das raízes finas. Essa matéria seca apresentou uma fraca, porém significativa correlação negativa com a quantidade de água no solo, o que evidencia que a redução da matéria seca nas raízes finas foi causada pelo aumento da disponibilidade de água resultante do uso de esterco. O uso de esterco de caprinos também levou a um aumento notável no volume dos tubérculos. Ao contrário das raízes finas, o crescimento do tubérculo não apresentou resposta à quantidade de água no solo, mas mostrou significativa correlação com a densidade do solo e a porosidade total. Após a aplicação do esterco, o solo apresentou uma redução em sua densidade e aumento na porosidade, o que levou a um aumento no volume do tubérculo.

A ausência de efeito dos tratamentos no crescimento do caule e no índice de sobrevivência, assim como um efeito negativo no crescimento de raízes finas das mudas de *S. tuberosa* devido ao aumento na quantidade de água indicam que o material vegetal usado é provavelmente selvagem e muito bem adaptado à escassez de água e de nutrientes de seu bioma.

Para desenvolver um sistema de manejo para *S. tuberosa* e promover um avanço na pesquisa sobre essa espécie, é necessário focar na domesticação e cultivo das mudas. É preciso desenvolver um cultivo confiável com colheita estável e menor período entre a germinação e aparição dos primeiros frutos assim como manter disponível material vegetal geneticamente homogênico. Do contrário, pesquisas sobre *S. tuberosa* continuarão a apresentar falhas devido a diferentes respostas de diferentes genótipos. Além disso, o potencial agroindustrial postulado de *S. tuberosa* não servirá como alternativa à estratégia de uso da terra para ajudar a mitigar a degradação na Caatinga se não gerar benefício monetário viável e a curto período para seus habitantes.

Notes on Publications

This cumulative dissertation is based on four scientific articles submitted to international peer-reviewed journals. At the date of the submission of this dissertation, the four articles have been published. These four article are:

Chapter 2:
Mertens, J., Almeida-Cortez, J.S., Germer, J., Sauerborn, J. (2015): Umbuzeiro (*Spondias tuberosa*): A Systematic Review. Rev. Bras. Ciênc. Ambient. 36, 179–197. doi:10.5327/Z2176-947820151006

Chapter 3:
Mertens, J., Germer, J., Siqueira Filho, J.A., Sauerborn, J. (2016): *Spondias tuberosa* Arruda (Anacardiaceae), a Threatened Tree of the Brazilian Caatinga? Braz. J. Biol. Ahead of print. doi:10.1590/1519-6984.18715

Chapter 4:
Mertens, J., Germer, J., Araújo Filho, J.C., Sauerborn, J. (2017): Effect of Biochar, Clay Substrate, and Manure Application on Water Availability and Tree Seedling Performance in a Sandy Soil. Arch. Agron. Soil Sci. 63, 969–983. doi:10.1080/03650340.2016.1249473

Chapter 5:
Mertens, J., Germer, S., Germer, J., Sauerborn, J. (2017): Comparison of Soil Amendments for Reforestation with a Native Multipurpose Tree Under Semiarid Climate: Root and Root Tuber Response of *Spondias tuberosa*. For. Ecol. Manag. 396, 1–10. doi: 10.1016/j.foreco.2017.04.010

A list of additional publications, to which I contributed as coauthor or first author and developed in the context of this dissertation, but not considered in the main section is placed in the Annex.

List of Abbreviations

α	Probability / significance level of post-hoc tests
α*	Ratio between the field-saturated soil hydraulic conductivity and the field-saturated matric flux potential
AC	Air capacity
AFLP	Amplified fragment length polymorphism
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
a.s.l.	Above sea level
APAC	Agência Pernambucana de Águas e Clima / Pernambuco State Agency for Water and Climate
AWC	Available water capacity
B	Boron
BA	Bahia
BAP	6-Benzylaminopurine ($C_{12}H_{11}N_5$), plant hormone
BGU	Banco germoplasma do Umbuzeiro / Germplasm Bank of Umbuzeiro
BMBF	Bundesministerium für Bildung und Forschung / German Federal Ministry of Education and Research
BSh	Hot semiarid climate
B.P.	Before Present
C6/36 cells	Cell line extracted from *Aedes albopictus* larval tissue
C	Carbon
Ca	Calcium
CAL	Calcium-acetate-lactate
CEC	Cation-exchange capacity
Cu	Copper

°Bx	Degrees Brix
DENV	Dengue virus
Embrapa	Empresa Brasileira de Pesquisa Agropecuária / Brazilian Agricultural Research Corporation
FC	Field capacity
FDR	Frequency domain reflectometry
GIMP	GNU Image Manipulation Program
GIS	Geographic information system
IAS	Invasive alien species
IBA	Indole-3-butyric acid ($C_{12}H_{13}NO_2$), plant rooting hormone
IBGE	Instituto Brasileiro de Geografia e Estatística / Brazilian Institute of Geography and Statistics
IUCN	International Union for Conservation of Nature
K	Potassium
K^{CAL}	Plant available potassium
K_{fs}	Field-saturated soil hydraulic conductivity
MAD	Median absolute deviation
Mg	Magnesium
Mn	Manganese
MS0	Murashige and Skoog medium, plant growth medium
N	Nitrogen
NaCl	Sodium chlorid
Φ	Total porosity
p	Probability / significance level of ANOVA and ANCOVA
P	Phosphorus
P^{CAL}	Plant available phosphorus

PE	Pernambuco
PPMCC	Pearson product-moment correlation coefficient
PWP	Permanent wilting point
ρ_b	Bulk density
ρ_p	Particle density
REML/BLUP	Restricted maximum likelihood / best linear unbiased prediction mixed model
RLD	Root length density
S	Sulfur
SD	Standard deviation
SDTF	Seasonally dry tropical forest
sp.	Species
spp.	Species pluralis
SUDENE	Superintendência de Desenvolvimento do Nordeste / Superintendency for the Development of the Northeast
θ_a	Available water capacity
θ_{fc}	Water content at field capcity
θ_{pwp}	Water content at permanent wilting point
TN	Total nitrogen
v/v	Volume per volume
w/	with
w/o	without
w/w	Weight per weight
WDPT	Water drop penetration time
WRB	World Reference Base for Soil Resources
Zn	Zinc

1. General Introduction

1.1 Caatinga, home of a seasonally dry tropical forest

The denotation dry tropical forest is based on the revised life zone classification coined by Holdridge (1967, 1947), which was introduced after he considered former classification systems by Köppen (1936, 1900) and Thornthwaite (1931) inappropriate for tropical latitudes (*Holdridge et al.*, 1971). Based on his diagram for the classification of world life zones or plant formation (*Holdridge*, 1967), dry tropical forests occur where the mean annual biotemperature♠ is greater than 17°C, the annual precipitation ranges from 250 to 2000 mm, and where the ratio of evapotranspiration and precipitation is greater than one. The seasonality, with a 4 – 6 months dry season, is the most distinctive character of the dry forests (*Dirzo et al.*, 2011), thus the term seasonally dry tropical forest (SDTF) is commonly used. Due to the seasonality, SDTFs are mostly deciduous forests dominated by woody legumes (*Mogni et al.*, 2015). They occur in areas between evergreen tropical rain forests and dry savannas and deserts, and are abundant in the paleotropics as well as in the neotropics (*Gerhardt and Hytteborn*, 1992; *Khurana and Singh*, 2001). According to Murphy and Lugo (1986) 42 % of the tropical and subtropical forests area are SDTFs, an area of 1,048,700 km^2 estimated in 2006, of which 67 % is located within the neotropics (*Miles et al.*, 2006). Whereas only 14 % of publications on neotropical forest environments between 1945 and 2004 focused on SDTFs (*Sánchez-Azofeifa et al.*, 2005). The low scientific interest of this tropical forest biome has led to serious lack of understanding of the world's biodiversity, the ecosystem services the SDTFs provide, and the anthropogenic threats they face (*Dirzo et al.*, 2011). The original or potential extent of SDTF might be even greater than present-day coverage, as it is assumed, that savannas and xeric shrublands evolved from disturbed SDTFs (*Murphy and Lugo*, 1986). The transformation process and loss of SDTFs might be still ongoing, since 97 % of the remaining SDTF are at risk due to climate change, fire, forest fragmentation, conversion to agricultural land, and other human activities (*Miles et al.*, 2006). According to these authors, natural and anthropogenic threats occur simultaneously and amplify the risk, and differ in various regions. For instance the African SDTFs face mainly

♠Biotemperature is defined as the annual mean temperature within the growing season. It is computed from the monthly mean temperature only considering monthly means > 0°C and < 30°C.

threats of fire and habitat fragmentation, whereas in the Americas, climate change is the biggest threat.

Over 50 % (568,400 km^2) of present-day worldwide SDTF cover is located in South America (*Miles et al.*, 2006). The South American SDTFs form a long arch around the Amazon basin from northeast Brazil to the Caribbean coasts of Colombia and Venezuela (*Caetano et al.*, 2008). With an area of approximately 522,700 km^2 as estimated in 2010, the largest remaining SDTF nuclei in South America is found within the 845,000 km^2 encompassing Caatinga biome in northeast Brazil (*Beuchle et al.*, 2015; *IBGE*, 2004; *Queiroz*, 2006). Considering the regional climate the Caatinga biome is likely to have been covered entirely with SDTF (sensu *Holdridge*, 1967), but lost due to anthropogenic pressure (see following sections). The name Caatinga is derived from the Tupi-Guarani language and means “white forest”, referring to the shiny grayish-white bare-branched trunks of the SDTF during the dry season (*Prado*, 2003). The climate in the Caatinga biome is defined as hot semiarid, and classified as BSh according to Köppen-Geiger, with little and erratic precipitation, which varies strongly seasonal and annual, and droughts are numerous and serious (*Cunha et al.*, 2015; *Leal et al.*, 2005; *Untied*, 2005). The annual precipitation ranges from 250 to 900 mm, with favored geographical locations such as slopes causing relief precipitation and in the proximity to the Atlantic Ocean, annual precipitation reaches 1500 mm (*Prado*, 2003; *Sampaio*, 1995). Whereas, 50 % of the Caatinga area receives < 750 mm precipitation, and up to 70 % of annual precipitation occurs during three to five consecutive

Figure 1.1: Location of the Caatinga (magenta polygon) in Brazil. Modified from Stöckli *et al.* (2005) after IBGE (2004).

months during the southern hemisphere summer from November until June (*Leal et al.*, 2005; *Sampaio*, 1995). Simultaneously, the evapotranspiration in the Caatinga is high, above 2000 mm per year, and the average annual temperature ranges from 23°C to 27°C with little monthly variation, < 5°C (*Sampaio*, 1995). The low levels of precipitation combined with high evapotranspiration lead to negative water balance during 7 to 11 months per year (*Menezes et al.*, 2012). Due to the great regional variation of precipitation combined with different site conditions, such as soil depth and type, the Caatinga vegetation is heterogeneous (*Costa et al.*, 2007; *Prado*, 2003; *Silva et al.*, 2015). It ranges from dry thorn forest to open shrubby vegetation, with a seasonal herbaceous layer (*Costa et al.*, 2007). Therefore Prado (2003) suggests the term Caatingas is more appropriate since it meets the plurality of vegetation types within the Caatinga and to avoid confusion, as Caatinga is also used as a geographical term. In this study the term Caatinga always refers to the biome, dominated by SDTF vegetation, within the boarders constitute by IBGE (2004) (Figure 1.1).

To date a total of 318 endemic species have been identified in the Caatinga, which accounts for 34 % of its known abundant vegetation (*Giulietti et al.*, 2004). The 318 species are mainly found among the Fabaceae (80), Cactaceae (41), Scrophulariaceae (3), Malpighiaceae (2), and Asteraceae (2) families (*Giulietti et al.*, 2004). The actual number of endemic species is likely to be much higher as the number of species is generally underestimated in the Caatinga since only 41 % of the Caatinga have ever been scientifically surveyed (*Albuquerque et al.*, 2012; *Costa et al.*, 2007; *Tabarelli and Vincent*, 2004). Therefore the level of endemism could be even higher and demonstrates the plight of a scientifically neglected SDTF within the scientifically neglected Caatinga biome. For instance by means of sampling and knowledge indexes based on publications on invertebrates published between 1985 and 1999 J. C. Santos *et al.* (2011) highlighted the high degree of neglect of the Caatinga in comparison to other Brazilian ecosystems.

Concerns about the poor conservation status of SDTFs in general also apply for the Caatinga in particular (*Leal et al.*, 2005; *Miles et al.*, 2006). The Caatinga transitioned from small-leaved, medium to tall, dry light forest that predominated in the Pre-Columbian era towards an open shrub forest. This transition was triggered by wood extraction, pasturing, and inappropriate land-use (*Costa et al.*, 2009; *Ribeiro et al.*, 2015). This anthropogenic pressure led to a loss of

50 % to 80 % of native vegetation cover, and 20 % of the area of the Caatinga biome already facing desertification (*Franca-Rocha et al.*, 2007; *Giongo et al.*, 2011; *Sá et al.*, 2010). This habitat degradation is ongoing, and the remaining native vegetation cover of the Caatinga is highly fragmented (*Beuchle et al.*, 2015; *Castelletti et al.*, 2003). Although the SDTFs in South America are supposed to be mainly threatened by climate change, the Caatinga vegetation seems to obtain resilience against climate change if its biodiversity is maintained (*Miles et al.*, 2006; *Oliveira et al.*, 2012; *Santos et al.*, 2014). Therefore, the conservation of biodiversity of the Caatinga vegetation, which is rich in endemism, is of high importance in order to sustain its ability to cope with future climate change. With only eleven reserves, which cover less than 1 % of the biome area, however, the Caatinga is currently poorly protected and the protection manners fail to protect the full range of its biodiversity (*Leal et al.*, 2005).

1.2 Land-use in the Caatinga and its impacts on the biome

The northeast of Brazil has a strong rural character with only ten urban centers, > 130,000 inhabitants, within its semiarid region. With approximately 31 persons/km^2, the Caatinga is one of the most densely populated semiarid regions worldwide (*IBGE*, 2005; *Salcedo and Menezes*, 2009). The water limited net primary production in the Caatinga, which is approximately 1100 g DM m^{-2} y^{-1} according to the climate calculation software New_LocClim provided by the Food and Agriculture Organization of the United Nations (FAO), is low compared to other regions in Brazil (*Grieser*, 2005). Limited water availability combined with recurrent water deficiencies during the growing season cause lower yields in the Caatinga when compared across the country. Therefore agricultural active Caatinga dwellers commonly combine crop

Figure 1.2: Caatinga vegetation after onset of rainy season in the foreground. Irrigated coconut plantation in Apolônio Sales, PE in the background. Own picture.

production and animal husbandry in order to compensate for crop shortfall (*Salcedo and Menezes*, 2009; *Sampaio*, 1995).

Crop production historically was based on a rain-fed shifting cultivation after slash-and-burn (*Tiessen et al.*, 1998). Major crops in the rain-fed cultivation, which consists predominantly of subsistence agriculture smallholders, are beans (*Phaseolus vulgaris* L.), maize (*Zea mays* L.), cassava (*Manihot esculenta* Crantz), and sweet potatoes (*Ipomoea batatas* (L.) Lam.) (*Cavalcanti*, 1999; *Salcedo and Menezes*, 2009; *Sampaio*, 1995; *Sietz et al.*, 2006; *The World Bank*, 1998). This agricultural practice is susceptible to the recurrent droughts and holds a great risk of famine among family farmers and smallholders in the Caatinga and kept them in poverty (*The World Bank*, 1998; *Untied*, 2005). In order to diminish rural poverty, to promote rural development and consolidate agricultural lands in the Caatinga, the Brazilian government started to implement irrigation farming along the banks of the São Francisco river in the 1970s. The implementation of irrigation farming became feasible due to the construction of six hydro-power dams along the 2,830 km long stream since the 1950s (*The World Bank*, 1998; *Untied*, 2005). This lead to a dissociation of the agricultural structure in the Caatinga into intensive modern export oriented irrigation farming, primarily with perennials such as mango (*Mangifera indica* L.) and grape (*Vitis vinifera* L.) and irrigated or rain-fed farming by smallholders as well as subsistence farming. With the new possibility on hand to irrigate smallholders and family farmers extended and diversified their production to even crops with high water demand like watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai), tomato (*Solanum lycopersicum* L.), pepper (*Capsicum* L.) (*Untied*, 2005) as well as perennials such as banana (*Musa spp.)*, coconut (*Cocos nucifera* L.) and mango (*personal observation*) in order to serve the regional and national market. According to an agricultural census in 2006, already 9,349 km^2, 1 % of its area, has been irrigated within the Caatinga (*IBGE*, 2009). However, irrigation farming can not expand much further as only 2 to 3 % of the Caatinga area is considered appropriate for irrigation (*Sampaio*, 1995; *Tiessen et al.*, 1998). Despite this effort made by the Brazilian government to consolidate the agriculture within the Caatinga, smallholders with farm sizes < 100 ha are still the majority. These smallholders are still facing a severe limitation of their agricultural production potential due to limited access to productive land, water, infrastructure, and markets (*Sietz et al.*, 2006). These limitations generate a further demand for agricultural land and force farmers to extend their production into less productive areas (*Gomes*, 2001). Increased production on less productive land increases the pressure on natural resources and reduces the yields ultimately, as newly cleared areas become infertile and unprofitable after approximately five years due to decline of soil carbon content (*Gomes*, 2001; *Tiessen et al.*, 1998).

Traditionally, extensive animal husbandry is widespread since the 18th century and almost all Caatinga areas are affected by free grazing and browsing of cattle (*Bos taurus* Linnaeus), domestic goats (*Capra aegagrus hircus* Linnaeus), sheep (*Ovis gmelini aries* Linnaeus) as well as released domestic donkeys (*Equus asinus asinus* Linnaeus) (*Gonçalves Júnior*, 2011; *Sampaio*, 1995; *Schulz et al.*, 2016; *Tiessen et al.*, 1998). Among the livestock in the Caatinga, goats and sheep are better adapted to the climate and fodder availability than cattle, and form an important and stable support for the livelihood of Caatinga dwellers (*Gonçalves Júnior*, 2011). The Caatinga used to exhibit the biggest herd of domestic goats in Brazil, in 2014 approximately 8 million individuals, as well as 10 million sheep (*IBGE*, 2015; *Leal et al.*, 2003). The number of cattle within the Caatinga was estimated with 22 million individuals in 2014 (*IBGE*, 2015). Drumond *et al.* (2004) reported stocking rates for sheep or goats of 0.3 – 1 individual per hectare and cattle 0.05 – 0.06 individual per hectare for which the native Caatinga vegetation, that lacks grazing resistance (*Leal et al.*, 2003; *Santo et al.*, 2012), can sustain. Based on the stocking rate for goats and sheep, the land requirement within in the Caatinga of the small ungulates is already approximately 600,000 km^2, 71 % of the biome's area. Hence, animal husbandry at current animal density makes forage production essential. Species planted for forage production are human introduced C_4 grasses from the genera *Cenchrus*, *Urochloa*, *Andropogon* as well as other alien species such as *Atriplex nummularia* Lindl., *Opuntia*

Figure 1.3: Vegetation cover on a shallow rocky Luvisols under browsing at onset of rainy season. Picture from Mira Siemann with kind permission.

ficus-indica Mill., and *Prosopis juliflor*a (Sw) DC. (*Alves et al.*, 2007; *Giulietti et al.*, 2004; *Pasiecznik et al.*, 2001).

Besides crop production and animal husbandry and regardless of illegality, wood extraction of native trees for purposes such as charcoal production is still a common land-use strategy in the Caatinga (*Ramos et al.*, 2008; *Ramos and Albuquerque*, 2012; *Ribero Filho et al.*, 2012; *Sá e Silva et al.*, 2009). It has high socioeconomic importance, as fuelwood is considered the second largest energy source for rural communities in the Caatinga in which 50 % of its population rely on fuelwood or charcoal as an energy source (*Campello et al.*, 1999; *Ramos et al.*, 2008).

The combination of extensive animal husbandry, crop production, and wood extraction poses a severe threat to the native vegetation of the Caatinga, and is responsible for a significant loss of its native vegetation cover (see Chapter 1.1). Vieira *et al.* (2013) denoted the cropped areas in the semiarid Brazilian Northeast in 2000 with 57 % or 1,024,621 km^2, which was a 28 % increase since 1993[♣]. Since the prevailing cropping systems cause decreasing soil carbon stocks, which leads to soil infertility and fewer yields under semiarid conditions, further clearing for new cropland is inevitable (*Giongo et al.*, 2011; *Sacramento et al.*, 2013; *Sharma et al.*, 2005). Additionally, improper irrigation schemes, in which lacking or faulty draining systems lead to soil salinization, cause the loss of arable land in the Caatinga as well (*Castelletti et al.*, 2003; *Untied*, 2005). Due to this continuous demand for agricultural land, it can be assumed that the cleared and cropped area in the semiarid Northeast today exceeds 1,024,621 km^2 as stated for 2000 by Vieira *et al.* (2013). Ongoing clearing and loss of native vegetation results in severe consequences for the Brazilian semiarid region. A significant loss of biodiversity, associated with the loss of resilience of the Caatinga to climate change as well as a loss of global biodiversity (see Chapter 1.1), and the loss of native vegetation cover boosts the current regional climate change towards a dry climate which facilitates desertification within the Caatinga (*Oyama and Nobre*, 2004; *Silva*, 2004). Browsing and grazing in the Caatinga negatively affect seedling density and seedling species richness (*Marinho et al.*, 2016) and presumably restrains the natural generative regeneration of the emblematic species *Spondias tuberosa* Arruda.

♣The study area covered 1,797,123 km^2, which was defined as the Brazilian semiarid region by *Superintendência de Desenvolvimento do Nordeste* (SUDENE) and exceeds the area of the Caatinga biome defined by *Instituto Brasileiro de Geografia e Estatística* (IBGE). However a similar rate of cropped area within the Caatinga is likely (*Castelletti et al.*, 2003).

Grazing also has a severe impact on soil fertility in the Caatinga, especially soil carbon stocks. Schulz *et al.* (2016) observed a significant reduction of soil carbon stocks in the upper 5 cm under high grazing intensity compared to light grazing intensity or no grazing. The authors concluded that grazing releases substantial carbon from the Caatinga soils and consequently hampers C sequestration in the biome. In addition, animal husbandry threatens the native Caatinga vegetation further due to the human introduced fodder plants. One third of all invasive alien species (IAS) in the Caatinga today are human introduced fodder plants out of the Poaceae and Fabaceae family (*Almeida et al.*, 2014). A notorious IAS out of the Fabaceae family is *P. juliflora,* which ranked as the most invasive plant species in the Caatinga (*Fabricante*, 2013). The species was introduced to Brazil in the 1940s on grounds of its multiple benefits and simultaneously fast-growing characteristic as well as its tolerance against arid conditions and against saline soils (*Cunha and Gomes*, 2012; *Pasiecznik et al.*, 2001). According to Pasiecznik *et al.* (2001) *P. juliflora* serves as a source of fodder, non-timber products, fuelwood, timber, and is associated with soil rehabilitation properties. Today, *P. juliflora* has virtually spread throughout the entire Caatinga along degraded river banks, and disturbed Caatinga sites and poses a severe threat to the native Caatinga vegetation (*Nascimento et al.*, 2014; *Pegado et al.*, 2006). The presence of *P. juliflora* significantly increases seedling mortality of native woody species as well as their vigor (*Nascimento et al.*, 2014). However, the hampering mechanism remains uncertain, whether it is due to allelopathy or due to direct competition for light, water, nutrients, or a combination thereof.

1.3 Problem statement

The present study was conducted within the framework of the German-Brazilian joint research project INNOVATE (**In**terplay among multiple uses of water reservoirs via in**nov**ative coupling of **a**quatic and **t**errestrial **e**cosystems), that is funded by the German Federal Ministry of Education and Research (BMBF) under project number 01LL0904B. The aim of this project was to optimize the multiple uses of man-made reservoirs using the example of the Itaparica reservoir at the middle reaches of the São Francisco river in the Brazilian semiarid Northeast. The holistic project targets were to increase the overall productivity of the ecosystem, to reduce greenhouse gas emissions, and to maintain biodiversity.

The damming of the São Francisco river in the late 1980s led to a resettlement of 5,192 families within the municipality Petrolândia bordering the Itaparica reservoir, of which 34 % were farming families that were compensated with lots in projected irrigation schemes for their loss of arable land on fertile alluvial soils along the now inundated river margins (*The World Bank*, 1998; *Untied*, 2005). The delayed, still ongoing allocation of lots in the irrigation schemes, and inappropriate irrigation technologies led to manifold social-economic and environmental problems (*Sobral et al.*, 2007; *The World Bank*, 1998). The Environmental problems primarily appear as soil degradation by salinization due to poor irrigation management, which leads to a reduction of the overall productivity of the agroecosystems, as well as the accumulation of mineral fertilizer and agrochemicals in the soils and water body (*Ministério do Meio Ambiente*, 2005; *Sobral et al.*, 2007; *The World Bank*, 1998). Due to reduced productivity resulting of soil degradation, irrigated lots get reallocated (*Sobral et al.*, 2007) and animal husbandry as additional income is wide spread in the municipality (see Chapter 1.5). This prevailing land-use with steady demand for new agricultural land and grazing pressure impacted the native vegetation within the municipality strongly, as native SDTF is only found on 125 ha, and 1,433 ha are already facing degradation, such as salinization, and desertification (*IBGE*, 2009). Due to the limitation of soils appropriate for irrigation within the Caatinga (see Chapter 1.2), and limited financial and human resources in order to implement highly advanced irrigation systems (*Hagel et al.*, 2014; *Sobral et al.*, 2007; *The World Bank*, 1998), the extension of irrigated farming is no resort in order to maintain livelihood of farming families. Thus, an alternative land-use strategy is imperative, to avoid further habitat degradation as well as to maintain or even improve the overall productivity of the agroecosystems. Such an alternative could be the cultivation of native or endemic multipurpose trees on disturbed Caatinga sites, with non-timber products in focus, such as *Spondias tuberosa* or *Ziziphus joazeiro* Mart.. Besides both are known as a fodder source, extracts from the bark and fruits of *Z. joazeiro* serve as a base product for cosmetic and medical products, whereas *S. tuberosa* provides multiple benefits and includes a great potential for agro-industrial exploitation (*Lima*, 1996). Both trees are associated with improving soil quality on cleared Caatinga sites or in silvopasture systems (*Wick and Tiessen*, 2008). Therefore these trees could additionally function as nurse plants to halt the habitat degradation and even nurse the Caatinga back to health (*Moura et al.*, 2013). The use of *S. tuberosa* should be preferential, due to its direct contribution to human diet and its regional social-cultural importance (*Monteiro*, 2007; *Neto et al.*, 2010). However, at this point a scientifically backed cropping system for *S. tuberosa* is lacking.

1.4 Aim and objectives

The present study is based on five objectives:

(1) Compile and review all publications about the biology, and physiology of *S. tuberosa* as well as its agro-industrial and medical use accessible via the relevant databases, such as Google Scholar, SciElo, ScienceDirect, Scopus, and WorldWideScience.

(2) Evaluate based on literature the conservation status of *S. tuberosa*, whether it is threatened due to man-made and/or natural threats, which may lead to a reduced regeneration of the species.

(3) Investigate the potential of the soil conditioners biochar, clay substrate, and goat manure to improve physical soil properties of coarse-textured soil under semiarid conditions.

(4) Asses the impact of amelioration on the seedling establishment and development of *S. tuberosa.*

(5) Study the effect of amelioration on the seedling's root architecture.

The hypotheses of the study, deviated from objective (2) to objective (5) are:

(a) *S. tuberosa* suffers a hampered natural regeneration and its natural population is at risk to become extinct.

(b) Coarse-textured sandy soil exhibits (i) an increased field capacity (FC) as well as available water capacity (AWC), and (ii) an extended period in which the soil moisture exceeds the permanent wilting point (PWP) due to amelioration with biochar, clay-substrate or goat manure.

(c) Establishment and development of *S. tuberosa* seedlings improve due to improved AWC and prolonged period in which the soil moisture exceeds the PWP.

(d) Fine root growth of *S. tuberosa* is positively affected by improved soil hydrological properties but is hampered by mineral fertilizer applications.

(e) Increased soil water content promote root tuber growth of *S. tuberosa*.

The overall aim of the present study is, to provide scientific knowledge for an extensive cropping system for *S. tuberosa* on disturbed Caatinga sites. The utilization of *S. tuberosa* in such a cropping system may mitigate habitat degradation within the Caatinga.

1.5 Study area

The study area is located in the municipality Petrolândia, which encompasses 1,056 km^2, at the banks of the Itaparica reservoir in Pernambuco (S8°58'49.7", W38°13'06.0", 320 m a.s.l.) (*IBGE*, 2016). The prevailing climate is semiarid, BSh, with a modeled thirty year average temperature of 24.3°C and a mean annual precipitation of 438 mm (1982 – 2012) (*Climate-Data.org*, 2016). Today, approximately 775 families cultivate 3,490 ha of irrigated land in three different irrigation schemes, Apolônio Sales, Barreiras, and Icó-Mandantes (*personal communication with Fábio Luiz Menezes in* 2015, *secretary for agricultural and environment of the municipality Petrolândia*). According to the agricultural census in 2006

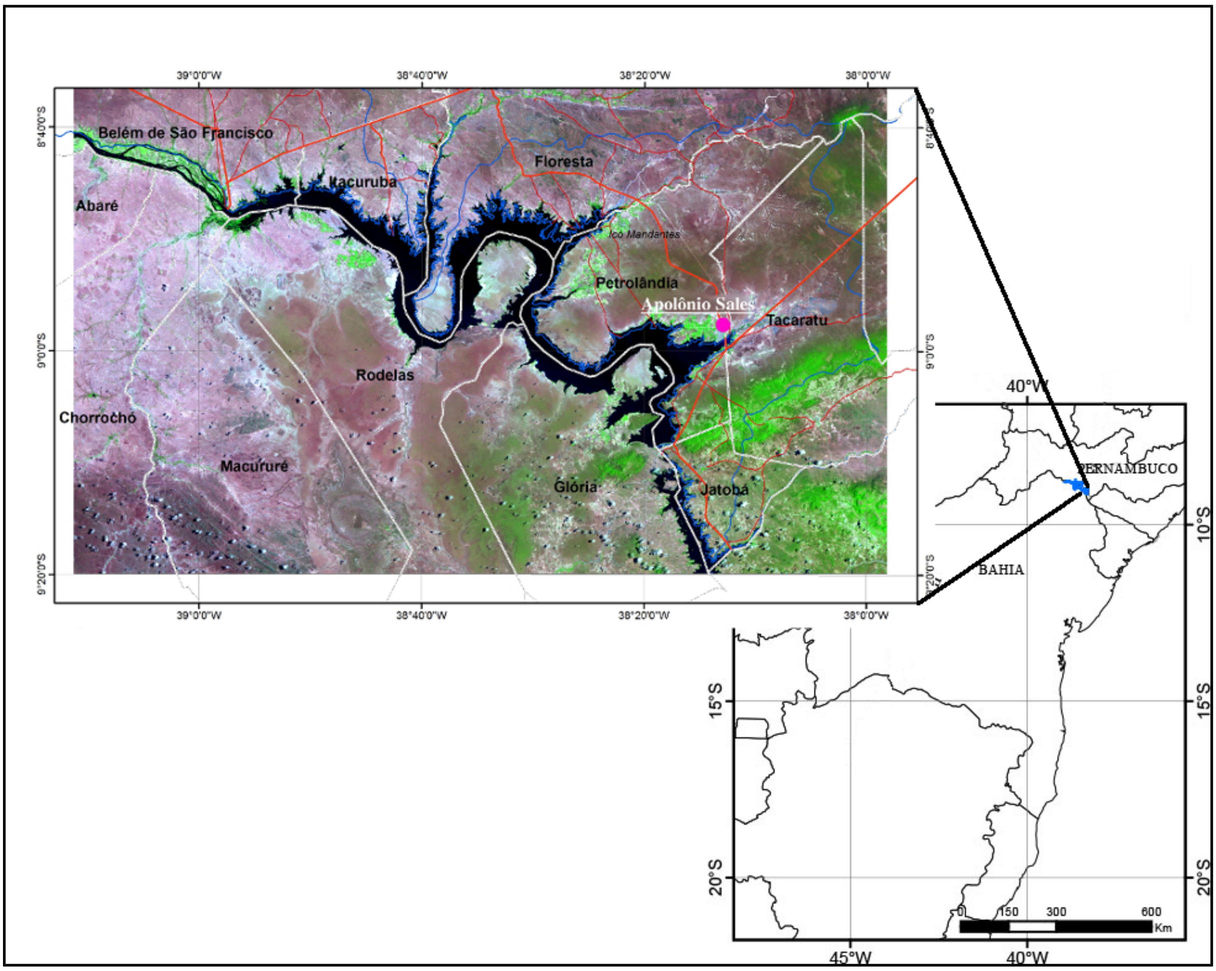

Figure 1.4: The Itaparica reservoir and the location of the irrigation scheme Apolônio Sales in municipality Petrolândia. Modified from Lopes (2012a, 2012b).

irrigated perennial crops were cultivated on 1,514 ha, irrigated annual crops were cultivated on 1,976 ha, and rain-fed cultivation of annual crops covered 2,977 ha. Including forage production cropped land in the municipality of Petrolândia summed up to 6,973 ha (*IBGE*, 2009). Small ungulates made up the majority of animal husbandry in the municipality Petrolândia. In 2014, 31,933 goats and 24,483 sheep were recorded, whereas the number of cattle was listed as 5,100 (*IBGE*, 2015). The experimental field was set up at the edge of the irrigation scheme Apolônio Sales on a disturbed Caatinga site (S8°57'24.1'', W38°15'00.4'', 330 m a.s.l.). Its native vegetation was degraded by foraging domestic animals as well as by fuelwood extraction. Evidences for these inferences were the presence of animal feces, especially of goats and donkeys, bite marks at Cactaceae, animal paths, and newly resprouted rootstocks (*personal observation*). The experimental field, encompassing approximately 4 ha, was fenced to avoid further grazing and browsing before the field experiment started, and the clearing of the native vegetation has been omitted. By means of a soil profile, the soil on site was classified as Arenosols according to the World Reference Base (WRB) (*IUSS Working Group WRB*, 2014), and it is poor on nutrients, and fine particle. A detailed description of the Arenosol is given in Chapter 4.

2. Umbuzeiro (*Spondias tuberosa*): A Systematic Review

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Abstract

Spondias tuberosa Arruda, a fructiferous tree endemic of semiarid Northeast of Brazil, provides several services to its ecosystem as well as to humans. It provides feed for wild animals as well as for domestic ruminants, and fruits rich in vitamins for human diet. It is an important source of additional income for family farmers and origin for traditional therapeutic medicine. Despite the importance of this tree in northeastern Brazil, limited scientific effort have been realized so far towards a better understanding of the tree's physiology and interaction within the ecosystem. Earlier studies about *S. tuberosa* focused on phenology, physiology, population genetics, management practices, and socioeconomic aspects. Due to the lack of breeding and cloning programs, physiological studies and management trials were based on heterogenic plant material, which leads to ambiguous results. In order to progress in *S. tuberosa* research, especially for its genetic conservations well as its agro-industrial exploitation, basic breeding and intensified genetic research is urgently required. Despite the few publications on *S. tuberosa*, the tree can be considered scientifically neglected, particularly if compared to other members of the Anacardiaceae family.

Keywords: Umbuzeiro, Caatinga, fruit tree, multipurpose tree, ecosystem service.

Published in *Revista Brasileira de Ciências Ambientais*, 36, 179 – 197, 2015. The electronic version of this article is the definitive one, available at: http://dx.doi.org/10.5327/Z2176-947820151006. With kind permission of Revista Brasileira de Ciências Ambientais.

2.1 Introduction

The fructiferous *Spondias tuberosa* known locally as Umbuzeiro, or Imbuzeiro belongs to the Anacardiaceae family (*Lima*, 1996), which contains several other important tropical and subtropical fruit-bearing trees such as *Mangifera indica* L., *Anacardium occidentale* L., *Pistacia vera* L., *Rhus coriaria* L., *Spondias mombin* L., and *Spondias purpurea* L.. Out of the Anacardiaceae, the genus *Spondias* is one of the most important in the Brazilian context, because of its potential for agro-industrial exploitation (*Silva Junior et al.*, 2004; *Souza Almeida et al.*, 2007). *Spondias* includes 17 to 18 species with seven to nine species occurring in the neotropics (*Miller and Schaal*, 2005; *Silva Junior et al.*, 2004). Among these *S. tuberosa* is endemic to the semiarid northeast region of Brazil, which is covered with a deciduous, thorny woodland vegetation called Caatinga (*Cavalcanti et al.*, 2002a; *Cavalcanti and Resende*, 2006; *Prado and Gibbs*, 1993; *Reis et al.*, 2010; *Santos and Oliveira*, 2008; *Silva Junior et al.*, 2004; *Sousa Araújo et al.*, 2012). The common name Umbuzeiro is derived from the tupi-guarani indigenous word “ymb-u" which can be translated as “the tree, which gives water” (*Barreto and Castro*, 2010; *Epstein*, 1998). Its fruit is called Brazilian plum locally known as Umbu, Imbu, Ambu or Ombu (*Barreto and Castro*, 2010)). It is considered a sacred tree, which is associated with the fact that *S. tuberosa* starts to blossom and subsequently sprouts leaves before the onset of the wet season. The tree is worshipped by indigenous tribes in spiritual rituals due to these early signs of life in the otherwise dormant Caatinga at the end of the dry season (*Machado et al.*, 1997; *Monteiro*, 2007; *Nadia et al.*, 2007; *Neto et al.*, 2010). Due to its early blossom Almeida *et al.* (2011) claim *S. tuberosa* represents an important feed resource for pollinators as well as for nectar sucking animals during the dry season. Scientists affirm great economic benefits of *S. tuberosa* for local smallholders and families. Borges *et al.* (2007) found that during the fruit harvest season, fruit picking and selling provides jobs and a major source of income for the dwellers in the semiarid northeast region of Brazil. The fruit of *S. tuberosa* contributes significantly to household income (*Barreto and Castro*, 2010; *Drumond et al.*, 2001; *Reis et al.*, 2010). Moreover, *S. tuberosa* is considered a medicinal plant with high importance for indigenous tribes in the Caatinga (*Albuquerque et al.*, 2011, 2007). Irrespective of the significance of *S. tuberosa* for local communities and the environment of the Caatinga, the tree faces several natural and man-made threats, which affects its natural regeneration. According to literature, the problem of natural regeneration and a possible subsequent extinction of *S. tuberosa* seems to be highly multifactorial.

As *S. tuberosa* is not well known (*Narain et al.*, 1992), this work aims to raise attention to one of the economically most important native trees of the scientifically neglected semiarid northeast region of Brazil (*J. C. Santos et al.*, 2011). Since the late 1980s about 100 articles on *S. tuberosa* were published, which are accessible through Google Scholar, SciElo, ScienceDirect, Scopus, and WorldWideScience. Forty percent of the articles are published only in Portuguese language with an English abstract, which makes it difficult to reach a large scientific audience and may contribute to the fact that neither the public nor the scientific community is familiar with *S. tuberosa*. We reviewed the majority of the publications accessible through the above mentioned five databases mainly with regard to biology, physiology and management of *S. tuberosa*.

2.2 Phenology, abundance, and reproductive biology

S. tuberosa is an up to 9 m tall xerophytic tree with a stunted, and strongly branched trunk approximately 0.3 to 1.4 m in diameter, and a characteristic umbrella-like crown 10 m in diameter (*Cavalcanti*, 2008; *Lima*, 1996). The grayish trunk sheds its bark in rectangle shaped plates (*Lima*, 1996). The leaves are pinnate and of an uneven number of oval leaflets (*Epstein*, 1998; *Lima*, 1996). Seedlings of *S. tuberosa* develop a taproot system, which is substituted with fibrous root systems within the first ten years after germination. The horizontal growth of the root system in this period is greater than its vertical development (*Cavalcanti et al.*, 2010; *Neto et al.*, 2009), this leads to a shallow root system, which spreads underneath the canopy area and grows up to 1.0 to 1.9 m depth (*Cavalcanti et al.*, 2010; *Cavalcanti and Resende*, 2006). As an adaption to the semiarid climate, *S. tuberosa* forms root tubers, in which the tree is able to store water, minerals, and organic solutes (*Cavalcanti et al.*, 2010; *Duque*, 2004; *Epstein*, 1998; *Lima*, 1996). This adaption of the tree is essential for its survival during the dry season (*Cavalcanti et al.*, 2010; *E. C. de Silva et al.*, 2008), and to initiate the flowering before onset of the rainy season (*Lima Filho*, 2007; *Machado et al.*, 1997). An adult *S. tuberosa* tree can have several hundred tubers with a mean tuber weight of about 2 kg (*Cavalcanti et al.*, 2002b, 2008b). Cavalcanti and Resende (2006) investigated twelve adult *S. tuberosa* and found in average 907 tubers per tree with a mean tuber weight of 1.5 kg. Cavalcanti *et al.* (2010) observed in average 112 tubers per tree with a mean tuber weight of 0.9 kg while exploring the root system of ten

ten-year-old trees. Besides the age of the tree, average annual precipitation is a factor, which seems to affect the number of tubers per plant, as Cavalcanti *et al.* (2002b) observed a slight decrease in tubers per tree during the study period from 1995 to 1998,concomitant with an annual precipitation decrease from 348 mm to 147 mm on the experimental plot (*APAC*, 2015).

S. tuberosa is abundant throughout the entire semiarid Northeast of Brazil, in the states Piauí, Ceará, Rio Grande do Norte, Paraiba, Pernambuco, Alagoas, Sergipe, Bahia, and in northern Minas Gerais (*Epstein*, 1998; *Lima*, 1996). Santos (1997) assumes the five regions Tanquinho, Jeremoabo, and Ipupiara in Bahia, Petrolina in Pernambuco, and Pio IX in Piauí within the Caatinga as the origin of *S. tuberosa* due to the great phenotypical uniformity found within these regions. The tree requires a daily air temperature between 12°C and 38°C, relative air humidity between 30 % and 90 %, 2000 to 3000 insolation hours per year, and 400 mm to 800 mm of precipitation during the rainy season from November until February. Deep, free draining soils without stagnant moisture favor its growth (*Epstein*, 1998). Tree stand density of *S. tuberosa* varies widely within the Caatinga. The theoretical total population of *S. tuberosa* ranges from 21 million to up to 630 million individuals within an area of 845,000 km^2, which is covered by Caatinga. Yet Santos (1997) claims differences in climate and soil types in such a vast area did not influence evolution and phenotypic differentiation of *S. tuberosa*. Neto *et al. (2013, 2012)* confirmed this uniformity in phenotype for areas with different land use and management as well.

S. tuberosa is an andromonoecious tree with white panicle inflorescence ranging from 0.1 to 0.2 m in length (*Cavalcanti et al.*, 2002a; *Epstein*, 1998; *Lima*, 1996; *Nadia et al.*, 2007). The inflorescence is made of up to 155 flowers on average, of which 40 % are hermaphrodite and 60 % are male flowers (*Nadia et al.*, 2007). Almeida *et al.* (2011) found a slightly higher number of flowers per inflorescence, 176 on average, if *S. tuberosa* is located within an anthropogenic influenced site, such as pastures, crop fields and/or corn (*Zea mays* L.), beans (*Phaseolus vulgaris* L.) or cactus (*Opuntiafícus-indica* Mill.) plantations. Sixty percent of the male flowers are located at the base of the inflorescence, whereas 90 % of the hermaphrodite flowers are located towards the apex of the inflorescence (*Nadia et al.*, 2007). The inflorescence has a flowering duration of two to seven days (*Leite and Machado*, 2010; *Nadia et al.*, 2007). Depending on the region blossoms appear from September until April with a peak in November before onset of the rainy season (*Barreto and Castro*, 2010; *Cavalcanti et al.*, 2000; *Leite and Machado*, 2010; *Machado et al.*, 1997; *Nadia et al.*, 2007; *Neto et al.*, 2013). Neto *et al.* (2013) stated, that the bloom of *S. tuberosa* is negatively correlated with occurrence of precipitation.

S. tuberosa is not especially adapted to a specific pollinator. Up to 19 insect species were observed visiting the entomophily and self-incompatible inflorescence (*Almeida et al.*, 2011; *Leite and Machado*, 2010; *Nadia et al.*, 2007). The visitors included the following orders: Hymenoptera (Apidae, Pompilidae, Vespidae), Diptera, and Lepidoptera. The Lepidoptera are considered nectar thieves and their visit does not result in pollination (*Almeida et al.*, 2011; *Nadia et al.*, 2007). Barreto *et al.* (2006) investigated the pollen load of pollinators visiting *S. tuberosa* inflorescence. They found the sting-less bees *Trigona spinipes* Fabricius., and *Frieseomelitta doederleini* Friese, and the red paper wasp *Polistes canadensi* Linnaeus are the most important among them, as they were exclusively loaded with pollen of *S. tuberosa*.

Reported ratios of flowers to fruits per inflorescence of *S. tuberosa* indicate a very low fruit set. Almeida *et al.* (2011) observed 0.55 fruits per flower on average. Leite and Machado (2010) found 0.01 fruits per flower after natural pollination and in case of cross-pollination this ratio increased to 0.22 fruits per flower. Whereas Nadia *et al.* (2007) found 0.01 fruits per flower after natural pollination and 0.02 fruits per flower after cross-pollination. They also investigated the effect of a pollen donor and found no significant difference when pollen originated from hermaphrodite flowers or male flowers. As *S. tuberosa* flowers are self-incompatible and no biparental inbreeding was observed of the outcrossing species, the low fruit set is unlikely a result of reduced offspring fitness due to inbreeding (*Frankham*, 2005; *Keller and Waller*, 2002; *C. A. F. Santos et al.*, 2011; *Santos and Gama*, 2013).

The drupe is about 3.2 cm long with a diameter of 2.8 cm, and weighs about 15.4 to 21.2 g (*Narain et al.*, 1992; *Santos*, 1997). The form of the greenish-yellow fruit, which contains a greenish-white pulp covered by a thin skin, ranges from round to oval or oblong (*Lima*, 1996). Fruit weight is made up of approximately 58 % pulp, 21 % seed, and 21 % skin. The pulp pH is about 3.1 with 9.47°Bx, and the content of titratable acids is 1.1 %. One Hundred gram of eatable portion of the fruit contains 0.3 g ash, 1.5 g iron, 15.6 g calcium, and 27.9 g phosphorus (*Narain et al.*, 1992). Further, it is a source of several vitamins, such as vitamin B_1, B_2, B_3, A, and C (*Vidigal et al.*, 2011), and is one of few native natural vitamin C sources for human consumption in the driest regions of northeast Brazil (*Araújo et al.*, 2001).

Table 2.1: Floral characteristics of *Spondias tuberosa* according to Nadia *et al.* (2007).

Floral characteristics	Hermaphrodite flower	Male flower
Calyx (sepals)	5	5
Corolla (petals)	5	5
Short stamen/ anther	5/5	5/5
Long stamen/ anther	5/5	5/5
Apocarp	1	0
Ovary per flower	1	0
Pistil	1	1

The dispersal of *S. tuberosa* is exclusively zoochoric by native animals, such as gray brocket (*Mazama gouazoubira* Fischer), black-rumped agouti (*Dasyprocta prymnolopha* Wagler), collared peccary (*Pecari tajacu* Linnaeus), fox (*Dusicyon thous* Linnaeus), yellow armadillo (*Euphractus sexcinctus* Linnaeus), the argentine black and white tegu (*Tupinambis merianae* Linnaeus), greater rhea (*Rhea americana* Linnaeus), white-naped jay (*Cyanocorax cyanopogon*, Wied-Neuwied) as well as by human introduced cattle (*Bos taurus* Linnaeus) and goat (*Capra aegagrus hircus* Linnaeus) (*Azevedo et al.*, 2013; *Barreto and Castro*, 2010; *Cavalcanti et al.*, 2009a; *Cavalcanti and Resende*, 2003; *Griz and Machado*, 2001).

2.3 Physiology

Studies published about the physiology of *S. tuberosa* focus virtually only on its response to mineral fertilization, salt- and water-stress, and its juvenile development.

Drumond *et al*. (2001) tested in a field experiment the effect of phosphorus (P) and nitrogen (N) fertilization combined with irrigation on *S. tuberosa* seedling growth in the first 40 months after transplanting ten-months-old seedlings. None of the treatments in their experiment showed a significant difference in plant height due to the mineral fertilization or irrigation within their 40 months trial period. In contrast Melo *et al.* (2005) found a positive response of *S. tuberosa* seedling on phosphorus and nitrogen fertilization on shoot height, shoot diameter, above ground dry matter, leaf area, and tuber diameter in their experiment in a mesh greenhouse and calculated an optimal N and P dose of 99 $kg\ ha^{-1}$ and 15 $kg\ ha^{-1}$ respectively. Neves *et al.*

(2008b) stated based on a six-month pot experiment that the optimal P input for best shoot growth (height and diameter), canopy area, and dry matter of root system of *S. tuberosa* seedlings is approximately 281 mg dm^{-3}. They observed a negative effect on all assessed parameters beyond that input level.

Andrade *et al.* (2013) observed in a pot experiment a negative effect of N and Potassium (K) fertilization on the development of *S. tuberosa* seedlings, their rootstock and their survival. The authors concluded that, the applied N (350 – 2800 mg dm^{-3}) and K (1800 – 7200 mg dm^{-3}) doses reached for *S. tuberosa* toxic levels. Neves *et al.* (2007a, 2007b) observed in a pot experiment the highest dry matter production after application of 286 mg N dm^{-3} and 137 – 229 mg K dm^{-3}. Beyond these doses the authors observed a negative effect of N and K application on seedling growth as well. Lacerda *et al.* (2009) observed on their pot experiment a negative effect of N application on seedling growth already at 0.65 mg dm^{-3}. Further, they showed an increasing seedling growth due to increasing Boron (B) concentration in the growth substrate. The greatest seedling growth in the experiment was achieved when the seedling was supplied with 3 mg B dm^{-3}. Since the experiment was conducted with a combined application of N and B, the authors also observed a negative interaction of both. The authors supposed that this may have been the result of an ion antagonism. The experiments above were carried out under different growth conditions, pot versus field experiment, and differ significantly in the growth substrate used. It is difficult to come to a conclusion based on few publications.

In a liming experiment Neves *et al.* (2008a) demonstrated a positive effect of liming on seedling growth. An increased base saturation due to liming led to an increased content of Ca, Mg, and S in shoot and leaves of *S. tuberosa* seedlings, whereas the content of N, P, K, Cu, Fe, Mn, and Zn decreased.

Table 2.2: Leaf concentration of mineral nutriments if *Spondias tuberosa* seedling is balanced nutrient supplied.

Mineral nutriment	Quantity mg g^{-1} dry matter	Author
N	25.72 – 29.48	Neves *et al.* 2007b
P	1.52 – 1.92	Neves *et al.* 2008b
K	3.40 – 6.04	Neves *et al.* 2007a
Mg	2.80 – 3.26	Neves *et al.* 2008a
Ca	18.28 – 21.47	Neves *et al.* 2008a

Ferri and Labouriau (1952) and Ferri (1953) were the first authors discussing the internal water balance and stomatal behavior of *S. tuberosa inter alia* (*Lima Filho and Silva*, 1988). Lima Filho and Silva (1988) reevaluated stomatal resistance, transpiration and leaf temperature of *S. tuberosa* at the end of the dry season and after the onset of the wet season. Differences in leaf temperature between dry and rainy season could not be observed, as well as the observed vapor pressure deficit was similar in both seasons. In both periods the lowest stomatal resistance was recorded at 7:00 am followed by an increase, yet the increase in the dry season was more intense. The stomatal resistance during rainy season was maintained at a low value almost until 1:00 pm, when consequently a high transpiration was recorded. Lima Filho (2004) detected a second peak with high stomata conductivity with subsequent high transpiration rates and photosynthesis rates during the rainy season at 4:00 pm, in addition to high stomata conductivity in the morning recorded by Lima Filho and Silva (1988). Thus, *S. tuberosa* exhibits a two-peaked daily course of gas exchange. Since the stomatal resistance increased around 1:00 am, with decreased stomatal conductivity, even though environmental conditions were favorable for high transpiration, Lima Filho and Silva (1988) concluded *S. tuberosa* regulates its internal water balance according to a very strict and accentuated stomata behavior, especially under adverse conditions. Later, Lima Filho (2001) stated *S. tuberosa* has two different strategies to maintain favorable internal water balance. Under dry conditions, the author claimed, it maintains its internal water balance by expenses of water stored in the tubers and by restricted transpiration. Whereas during the wet season, the internal water balance is maintained by short term osmotic adjustments, such as uptake of additional inorganic salts or the accumulation of organic solutes (*Lima Filho*, 2001). The very strict and accentuated stomatal behavior reported by Lima Filho and Silva (1988) and Lima Filho (2004, 2001) differs among various phenotypes of *S. tuberosa*, some phenotypes appear to be more sensitive than others (*Silva et al.*, 2009a) (the authors use the term genotype although the accessions in the Germplasm Bank of Umbuzeiro BGU were not categorized on genetic base (see Chapter 2.4)). Two of the tested phenotypes showed a correlation of stomatal behavior with air temperature, relative humidity, and vapor pressure deficit, one tested phenotype showed correlation with photosynthetic active radiation, whereas one phenotype did not show any correlation of stomatal behavior with the assessed environmental factors. The authors concluded that the observed differences in anatomical alteration in the different phenotypes, such as stomatal density, stomatal index, and stomatal aperture size, could not fully explain the physiological differences among the tested phenotypes. Changes in leaf water potential, concentration of carbohydrates, amino acids, and proline in leaves and root tubers as a response to intermittent drought differs in different phenotypes as well (*Silva et al.*, 2009b). The concentration of proteins in *S. tuberosa* leaves and root tubers did not vary neither due to induced drought nor due to different phenotypes in the same experiment. Since Silva *et al*. (2009b) observed high leaf water potential even though soil moisture reached the permanent wilting point, the strategy of maintaining favorable internal water balance by water stored in the tubers (*Lima Filho*, 2001) seems factual.

S. tuberosa seedlings show a negative response in growth on salt stress. However, when cultivated in a nutrient solution with a NaCl concentration up to 31 mM, it proved to be moderately tolerant to salinity (*Neves et al.*, 2004a). The authors assume that this moderate tolerance to salt stress is realized due to the tubers of the seedlings, which accumulates excess NaCl. E. C. de Silva *et al.* (2008) observed negative effects of salinity on the seedling growth if the NaCl concentration exceeds 50 mM. The authors could not detect a decreasing root/shoot ratio as reported by Neves *et al*. (2004a). Due to the increase of root/shoot ratio observed in their experiment, E. C. de Silva *et al.* (2008) state the salinity effects are more severe on the shoot growth than root growth, which implies the root system of *S. tuberosa* is less sensitive towards salt stress than observed in other crops, such as beans (*Seemann and Critchley*, 1985) or wheat (*Jbir et al.*, 2001).

2.4 Population genetics

In order to conserve genetic variation of *S. tuberosa*, Embrapa (Brazilian Corporation of Agricultural Research) Semiárido in Petrolina, Pernambuco, Brazil (Embrapa-CPATSA) established in 1994 a germplasm collection (Germplasm Bank of Umbuzeiro BGU) in its experimental site in the municipality of Petrolina. Until 2012 it contains 79 accessions with the last addition in 2002 (*Nascimento et al.*, 2012, 2002). The accessions were categorized based on fruit characteristics and tree habit (*Nascimento et al.*, 2002). The first approach studying the genetic variability of *S. tuberosa* was conducted in 2004 using a restricted maximum likelihood/best linear unbiased prediction (REML/BLUP) mixed model methodology (*Oliveira et al.*, 2004). After evaluating plant height, canopy diameter, basal trunk diameter, and number of primary branches of 42 trees from three different regions, the authors concluded the greater genetic variability is found within local *S. tuberosa* populations compared to the variability in between populations of different ecoregions. The first study on the genetic level of *S. tuberosa* was conducted by Santos *et al*. (2008), assessing the genetic variability with the amplified fragment length polymorphism (AFLP) method. Their results object the findings of Oliveira *et al.* (2004), as Santos *et al.* (2008) observed a high variability in between ecoregions whereas within local populations higher similarities were observed in the resulting dendrogram. The AFLP method was also used to determine the outcrossing rate of *S. tuberosa* (*C. A. F. Santos et al.*, 2011; *Santos and Gama*, 2013). In both studies, which combined AFLP with the mixed-mating model, a high heterozygosity in the offspring generation was observed. This observation signifies that *S. tuberosa* is predominantly an outcrossing species. Since the differential of the multi-locus outcrossing estimation and the single-locus estimation was small, a parental inbreed could not be observed. Concluding, Santos *et al.* (2008) and C. A. F. Santos *et al.* (2011) recommended numerous protection areas for *in situ* conservation of genetic variability of *S. tuberosa* or broad fruit sampling in various ecoregions for *ex situ* genetic variability conservation. The latter already exists in form of the BGU of Embrapa even though its accessions are categorized based on phenotype characteristics.

2.5 Management practices

For plantations a density from 39 to 100 plants ha^{-1} is recommended for *S. tuberosa* with a tree spacing ranging from 10 m x 10 m to 16 m x 16 m (*Epstein*, 1998). The suggested size of the planting hole is 40 cm x 40 cm x 40 cm or 50 cm x 50 cm x 50 cm and the refill earth should be enriched with 20 l of cow manure, 300 g of simple superphosphate, and 100 g of potassium-chloride - depending on the soil type and soil fertility (*Epstein*, 1998).

Seeds of *S. tuberosa* have naturally a very distinct dormancy, which remains an obstruction for commercial seedling production. Few, partly antithetic, research works investigated how the dormancy of *S. tuberosa* seeds can be overcome. The effect, which accounts for the natural reproduction as well as for agro-industrial exploration discussed in literature is the maturation of seeds after the abscission of the fruits. Araújo *et al.* (2001) showed a strong increase in germination after 24 months of seed maturation. This maturation period lead to a germination of 73.6 % compared to the germination of 22.8 % of freshly harvested seeds. According to the authors, already 12 months of maturation significantly increases the germination to 27.7 %.

According to Cavalcanti *et al.* (2006b) a maturation time of 24 to 48 months leads to the highest germination percentage between 60.0 % and 72.5 % within 30 days after sowing. Magalhães *et al.* (2007) tested the influence of 13 different maturation periods, 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, and 360 days. After a maturation period of 90 up to 210 days they observed the highest germination of 70 % and a decrease in germination beyond a maturation time of 300 days. A fourth work observed the highest germination between 120 and 210 days of maturation (*Lopes et al.*, 2009), which differs only slightly from the work of Magalhães *et al.* (2007) and confirms their findings. Besides the storage period, storage conditions, and fruit ripeness affect the germination, which were not consistent in the above publications (compare Chapter 2.8).

Methods to break the dormancy of *S. tuberosa* seeds discussed in literature with importance for agro-industrial exploration are mechanical, chemical and thermal scarification, and immersion in water or growth promoting solutions such as gibberellic acid, ethylene or cytokinin. Chemical scarification and thermal scarification are not appropriate methods to break the dormancy of *S. tuberosa* seeds. Seeds treated with these methods showed a significantly lower germination percentage than the control seeds (*Aragão et al.*, 2008). Lopes *et al.* (2009) did not detect any germination after the seeds were treated with H_2SO_4 for 10 minutes. Neither Lopes *et al.* (2009) nor Melo *et al.* (2012) observed any positive effect on germination due to treatment with growth regulating solutions. Immersion of the seeds in water for 24 hours slightly increased the germination (*Aragão et al.*, 2008), but the most appropriate method seems to be the mechanical scarification by a bevel cutting distal of the seed, introduced by Epstein (1998), to allow water to easily soak the seed. Lopes *et al.* (2009) and Aragão *et al*. (2008) observed the highest germination after such treatment. Yet Neto *et al*. (2009) and Melo *et al.* (2012) stated even mechanical scarification does not break dormancy of *S. tuberosa* seeds.

According to Cavalcanti *et al.* (2002a), the most suitable substrate for *S. tuberosa* germination and greater shoot height and shoot diameter is the actual Caatinga soil. Growth substrate made of soil and cattle manure (50:50 v/v) lead to the biggest canopy area and subsequent highest dry matter (*Cavalcanti et al.*, 2002a).

Besides the generative propagation *S. tuberosa* can be propagated by vegetative reproduction with stem cuttings (*Epstein*, 1998; *Lima*, 1996), which is of interest for the agro-industrial use of

S. tuberosa since the uncertain and time demanding germination will by skipped. *S. tuberosa* propagated by stem cutting is not prone to form root tubers and it is not recommended to plant such trees in areas with limited soil water availability (*Lima Filho*, 2007), unless such trees are placed in a plantation with additional irrigation. Melo *et al.* (1997) experimented with a different form of vegetative propagation in order to produce living germplasm for genetic conservation of *S. tuberosa*. They succeeded with micro-propagation of nodal segments of one-year-old seedlings on a Murashige and Skoog medium (MS0) (*Murashige and Skoog*, 1962) with 0.1 mg l^{-1} BAP (6-Benzylaminopurine, $C_{12}H_{11}N_5$) to obtain 2.2 new sprouts on average after one week of cultivation. In the control treatment, 1.5 shoots sprouted. They also tested IBA ($C_{12}H_{13}NO_2$), which seemed to hamper sprouting as did higher doses of BAP. Dutra *et al.* (2012) found IBA did not have a positive effect on growth of *S. tuberosa* in their experiment as well. Even though they claim IBA promotes root growth when used to propagate *S. tuberosa* by air layering, they could not show a significant effect of IBA concentrations on the development and growth of root tissue.

In 1990 and 1991 two works were published on successful grafting of *S. tuberosa* (*Mendes*, 1990; *Pedrosa et al.*, 1991), which seems to be a promising method for commercial seedling production, as grafted seedlings start to produce fruits after four years, whereas non-grafted seedlings bear fruits only after 10 years (*Mendes*, 1990; *Nascimento et al.*, 1993). Espíndola *et al.* (2004) tested how two different size classes (7 – 9 mm; 4 – 6 mm) of the scion, cleft graft, and splice graft affect the development of the grafted seedling. The viability of the seedlings after 15 days did not differ between the two grafting methods and the different methods had no influence on the development of the seedlings within the first 45 days. The authors did, however, observe that larger scions formed significantly more sprouts than the smaller ones. A similar effect of diameter was noted by Gomes *et al.* (2010), who investigated the effect of rootstock diameter as well as the grafting method on seedling development. They observed a positive effect in larger diameter rootstock on the growth of grafted seedlings within the first 120 days regardless to the grafting method. In their experiment, the success of the grafting was dependent on the chosen method. The fixation of the scion was significantly higher if the splice graft was conducted regardless to the rootstock diameter. This was already observed by Araújo and Neto (2002) in their experiment. Further, the author stated neither the physiological nor phenological state of a tree the scion is taken from, has influence on the success of grafting, which allows grafting throughout the entire year. Six months after germination, *S. tuberosa* seedlings are already able to be used as rootstock for grafting, and the ability will not change until the rootstock exceeds six years of age. After six years, the success rate of grafting reduces gradually (*Reis et al.*, 2010). The effect of grafting on the tuber production of *S. tuberosa*, as seen under stem cutting conditions, has not yet been investigated.

Narain *et al.* (1992) identified an absence of plantations of *S. tuberosa*. The fruit production of Brazilian plum is limited to extractivism. Neto *et al*. (2010) observed the management of *S. tuberosa* is limited to tolerance of native trees, fruit picking, and in particular cases, protection manners against an abundant epiphyte, *Tilandsia* sp. Also, little is known about pest and diseases of *S. tuberosa* and its fruits. Pests and pathogens associated with *S. tuberosa* are *Phasmatodea* spp., *Diabrotica speciosa* Germar, *Megalopyge lanata* Stoll, *Cryptotermes* spp., *Pinnaspis* spp., *Elsinoë* spp., *Septoria* spp., *Glomerella cingulata* (Stoneman) Spauld. & H. Schrenk, and *Guignardia* spp. (*Freire and Bezerra*, 2001; *Neves and Carvalho*, 2005; *Tavares et al.*, 1998). Two fruits flies, *Ceratitis capitata* Wiedemann, and *Anastrepha obliqua* Macquart, are associated with the Brazilian plum and are considered as postharvest pests (*Araujo et al.*, 2005; *N. M. D. O. E. Silva et al.*, 2008).

2.6 Economic aspects

S. tuberosa is considered a multipurpose tree, of which foliage is used as animal feed, fruits and root tubers contribute to human diet, provides fuel wood, additionally bark, bast and resin are utilized for therapeutic practices (*Albuquerque et al.*, 2007; *Epstein*, 1998; *Lima*, 1996; *Neto et al.*, 2010; *Sá e Silva et al.*, 2009). To ban the utilization of *S. tuberosa* as fuel wood, a draft law to prohibit felling the tree was introduced in 2004 (*Projeto de Lei No 3.548, DE 2004 - Dispõe sobre a proibição da derrubada do umbuzeiro em todo país, e dá outras providências.*, 2004).

The fruit itself is the most important product of *S. tuberosa*. It is consumed in Brazil *in natura* or processed as juice, sweet, jam, ice cream, and umbuzada (fruit pulp boiled with milk and sugar) (*Narain et al.*, 1992; *Neto et al.*, 2010). Frozen industrial processed fruit pulp is also exported to several European countries (*Narain et al.*, 1992). The reported annual yields of *S. tuberosa* vary largely. Santos (1999) observed in 16 trees yields ranging from 4.2 kg to 184.0 kg of fresh fruits per tree annually, with a mean of 61.5 kg. Cavalcanti *et al.* (2008b) reported annual yields ranging from 206.9 kg to 531.2 kg of fresh fruits per tree with a mean of 323.6 kg based on

66 trees. As Cavalcanti *et al.* (2011) noted an increase of fruit production due to additional irrigation, the observed wide range in fruit yield may primarily be caused by the great variation in precipitation throughout the Caatinga. Especially the precipitation in the beginning of the rainy season from November to December is very important for yield formation (*Cavalcanti et al.*, 2011). Fruit yield per tree increases in strong correlation to the canopy diameter (*Santos and Nascimento*, 1998). Thus, the variation in yield seems to be primarily defined by climatic factors and tree age.

Family farmers involved in Brazilian plum harvest in 2007 generated an averaged additional income of 670 BRL within 55 days of harvest, which equals about two minimum wages (*Cavalcanti*, 2008). If harvesting farmers or cooperatives additionally process the fruits, their benefits could increase due to adding value of about 1025 % (*Barreto and Castro*, 2010). In 2012 7979 t of Brazilian plum were harvested, which generated a monetary value of approximately 3,820,500 USD (Table 2.4). This underlines the economic importance of the Brazilian plum commercialization for the rural communities. Specially if processing is done in the communities. Using the root tubers of *S. tuberosa* seedlings to produce pickles could generate further income for Family farmers. Pickles produced of 120 days old seedlings cultivated in washed sand and pickled with salt and ascorbic acid show a high consumer acceptance (*Cavalcanti et al.*, 2004b). To produce the needed seedlings, the authors suggest to use seeds that remain from pulp or juice production as they are already available.

Table 2.3: Chemical composition of 100 g of the eatable portion of Brazilian plum, modified from Narain *et al.* (1992).

Constituents	
Moisture [g]	87.25
Fat [g]	0.85
Protein [g]	0.31
Crude fiber [g]	1.04
Total sugars [g]	5.38
Starch [g]	1.41
Tannin [g]	0.12
Ascorbic acid [mg]	15.80

Table 2.4: Quantity and value of Brazilian plum harvest in 2012 (*IBGE*, 2013)**.**

Federal State	Quantity t	Value 1000 BRL
Piauí	56	55
Ceará	38	53
Rio Grande do Norte	231	453
Paraíba	83	59
Pernambuco	403	281
Alagoas	34	25
Bahia	7010	6615
Minas Gerais	124	100

1 BRL ≈ 0.50 USD in 2012

A further branch of commercial exploration of *S. tuberosa* might be the oil obtained from seed kernels. The oil content of the kernels, about 56 %, is very high compared to cashew nut (46 %) or sesame seeds (49 %) (*Borges et al.*, 2007). The authors observed a favorable ratio of the oleic and linoleic fatty acids, and a high content of minerals. They suggested the oil of *S. tuberosa* may be an edible oil for food enrichment and even utilized as frying oil. Screening the oil for toxins or allergenic factors is pending.

The foliage of *S. tuberosa*, utilized as animal feed, has a slightly higher content of crude protein during the rainy season compared with other native Caatinga species, which makes it an interesting alternative animal feed (*Cavalcanti et al.*, 2004a; *Lima*, 1996). The crude protein content of the foliage drops by 31 % during dry season and consequently the in vitro digestibility drops from 46 % to 40 %. Cavalcanti *et al.* (2004a) quantified the amount of foliage consumed by Caprinae during wet and dry season per *S. tuberosa*. The authors observed that Caprinae consume approximately 19 kg foliage per tree during the rainy season and approximately 39 kg foliage per tree during the dry season and concluded that *S. tuberosa* is a very important alternative food source for animal husbandry in the semiarid Northeast of Brazil. During fruit season, *S. tuberosa* contributes considerably to animal nutrition too, as one goat consumes more than ten thousand fruits per fruit season, which equals approximately 131 kg of Brazilian plum (*Resende et al.*, 2004).

Table 2.5: Fatty acid composition of Brazilian plum and other oil plants, compiled from Borges *et al.* (2007), Ivanov *et al.* (2010), Wang *et al.* (2012), and Were *et al.* (2006).

	Fatty acid composition %					Ratio
	16:0	18:0	18:1	18:2	20:0	oleic/linoleic acid
Brazilian plum seeds	19.4	11.3	34.4	33.7	0.6	1/0.98
Sesame seeds	8.2	4.9	37.6	47.8	0.5	1/1.27
Peanuts	11.0	3.3	43.2	35.0	1.6	1/0.81
Soybean oil	17.0	5.2	16.0	47.6	1.4	1/2.98

2.7 *Spondias tuberosa*, a medical plant

Among the dwellers and indigenous tribes of the Caatinga, *S. tuberosa* is considered a medical plant (*Albuquerque et al.*, 2007; *Albuquerque and Oliveira*, 2007; *Almeida et al.*, 2010; *Júnior et al.*, 2011; *Neto et al.*, 2010). Interviews with local communities reveal, that in traditional therapeutic practices, bark, bast, leaves, fruits, roots, and resin of *S. tuberosa* are used to treat numerous symptoms, such as conjunctivitis, ophthalmia, venereal diseases, digestive problems, colic, diarrhea, diabetes, menstrual disturbances, renal infection, throat afflictions, kidney inflammation, tooth pain, and "not healing cut" (*Albuquerque et al.*, 2011; *Júnior et al.*, 2011). None of the publications above mentioned which plant parts are used for which purposes and whether the plant parts are utilized *in natura*, as extraction or infusion. The therapeutic efficacy of *S. tuberosa* drugs may be a result of the high content of tannins and flavonoids detected in bark and fruit, which are considered as wound-healing and anti-inflammatory active (*Sousa Araújo et al.*, 2008). The content of tannin and antioxidant activity varies in plants due to environmental, genotypic factors, and plant age as summarized by Sousa Araújo *et al.* (2012). The same authors investigated, whether different habitats influence the tannin content and antioxidant activity in *S. tuberosa*. They observed a significant difference in antioxidant activity due to collection site, whereas the tannin concentration did not show significant difference. Since other studies showed a correlation between tannin concentration and antioxidant activity (*Aoudia et al.*, 2013; *He et al.*, 2011), Sousa Araújo *et al.* (2012) concluded that the antioxidant activity of *S. tuberosa* might be influenced by other metabolites, whose production and accumulation is more sensitive to differences in habitat.

Besides traditional therapeutic practices *S. tuberosa* became the focus of academic medicine as well. In 1997, 75 Brazilian plant species, including *S. tuberosa*, were screened for anti-tumor active extracts (*Moraes et al.*, 1997; *Pessoa et al.*, 2006). Moraes *et al.* (1997) reported an inhibited growth of Walker's tumor by 18 % after treating with a crude hydro-alcoholic extract of the bark of *S. tuberosa*. Since the authors considered the extracts active if the inhibition exceeds 40 %, the extract of *S. tuberosa* was not considered anti-tumor active. *S. tuberosa* may provide a breakthrough for the development of an anti-dengue virus agent. The recently developed and tested anti-dengue virus vaccine, the Sanofi Pasteur dengue vaccine, provides protection against dengue virus type 1, 3, and 4 but does not provide significant protection against dengue virus type 2 (DENV 2) (*Bärnighausen et al.*, 2013). *S. tuberosa* research may not provide a solution for the vaccination dilemma, but it shows promising results for developing an anti-dengue virus agent. Silva *et al.* (2011) tested secondary metabolites, phenolic compounds, of *S. tuberosa* and *S. mombin* for their anti-viral activity against DENV 2. The authors identified two flavonoids in the leaf extract of the two *Spondias* species with anti-viral activity, rutin and quercetin, and only in *S. tuberosa* were both present (Table 2.6). Rutin and quercetin showed in vitro a viral inhibiting effect of DENV 2 in C6/36 cells of 68.42 % and 50 % respectively. Concluding, the author stated that rutin and quercetin extracted from *S. tuberosa* leaves have potential for the development of an anti-DENV 2 agent. However, further studies with other cell lines and *in vivo* survey are required to affirm the effectiveness of these flavonoids against DENV 2 (*Silva et al.*, 2011).

Table 2.6: Quantities of flavonoids in *Spondias* species, modified from Silva *et al.* (2011).

Compound	*S. mombin* mg g^{-1} extract	*S. tuberosa* mg g^{-1} extract
Rutin	n.d.[1]	53.38
Quercetin	41.56	169.76

[1]not detected

2.8 Conclusion

To date *S. tuberosa* is hardly domesticated (*Neto et al.*, 2012), and all experiments were virtually conducted with wild types and no homogeneous plant material is available. The highest uniformity in plant material was achieved by grafting *S. tuberosa* seedlings at Embrapa Semiárido. Even though the scions are obtained from the same tree as well as the seeds, which formed the rootstock, the grafted seedlings are genetically not identical. Because seeds from the same stock plant are genetically heterogeneous, which is caused by self-incompatible and outcrossing feature of the reproduction system of S. *tuberosa*. Still, some publications use the term clone or genotype erroneously for grafted *S. tuberosa* seedlings from Embrapa Semiárido. To our knowledge neither cloning nor breeding was successfully executed to date. Due to the lack of clones or hybrids, physiological studies conducted on *S. tuberosa* seedlings are difficult to interpret since observed outcomes may have resulted from the genetic diversity and not from applied treatments. Yet, grafting of *S. tuberosa* is the key method for its commercial propagation in tree nurseries to obtain refined seedlings for a fast fruit production.

Besides the heterogeneity of the used plant material, comparing existing results with each other faces further constraints, which we want to illustrate with the results from the P fertilization experiments and the seed maturation experiments. Consulting literature for the optimal P fertilization is a difficult task owing to the lack of methodological consistency among the studies. On the one hand field experiments and on the other hand pot experiments using different bases for calculating the fertilizer dose, per plant versus per hectare versus per soil volume. Whereof the calculation based on weight per volume is rather unorthodox. This makes it difficult to compare the results about the response of *S. tuberosa* seedlings on P fertilization. This shows a dilemma in *S. tuberosa* research, only few studies are available which are hardly comparable, as the used units for the fertilizer application are not standardized. A unit, which can be supposedly deduced from three P fertilization experiments published, is g $plant^{-1}$ which is not precise and an unserviceable unit.

The partly opposing findings for germination after seed maturation may result from the inconsistent conditions the seeds were stored during maturation. Araújo *et al.* (2001), Magalhães *et al.* (2007), and Lopes *et al.* (2009) stored the seeds under controlled conditions with 10°C, 22.5°C, 25°C respectively. Only Cavalcanti *et al.* (2002a) stored the seeds under ambient conditions in dry soil, which comes close to natural conditions seeds encounter in the Caatinga. The antithetic findings may also have occurred due to differences in the maturation of the fruits. Souza *et al.* (2005) observed a significant effect of degree of ripeness of the fruit itself on the germination of *S. tuberosa* seeds and the above mentioned authors did not comment on degree of ripeness of their experimental material or neglected this information. The results are difficult to compare due to different experimental set-ups and again a lacking consistent methodology.

The *S. tuberosa* research in general is not yet very advanced and lacks accessibility. For instance, Scopus shows only 58 hits for *S. tuberosa* in the time period between 1980 and 2015, whereas other wider distributed and economic more important members of the family Anacardiaceae, such as mango and cashew, generated 522 and 521 hits respectively in the same period. The lack of scientific work was also noted by Neves and Carvalho (2005) in their publication. The little availability of studies about *S. tuberosa* is present in all aspects of its research, and only a few researchers and research groups worked on *S. tuberosa*, which is reflected in the little number of different authors and their recurrence. Despite its economic and medical potential for northeast region of Brazil, we consider *S. tuberosa* scientifically neglected to date. In oder to progress in *S. tuberosa* research we suggest to focus on following research fields:

- Vegetative propagation/ cloning
- Breeding and establishing cultivars
- Management practices
- Utilization as medical plant and oil source

To increase the understanding of *S. tuberosa*, specially for its further agro-industrial exploitation and its medical use scientific effort is still required. To avoid a depletion of the natural *S. tuberosa* population efforts are required in breeding and management practices in order to shorten the time between germination and first fructification to make *S. tuberosa* plantations profitable. Simultaneously, efforts are required to understand *S. tuberosa* in its habitat, with its problematic reproduction in mind, in order to maintain and protect its genetic diversity.

Acknowledgements

This work was supported by the German-Brazilian joint research project INNOVATE (Interplay between the multiple uses of water reservoirs via innovative coupling of substance cycles in aquatic and terrestrial ecosystems). The project is funded by the German Federal Ministry of Education and Research (BMBF)under project number 01LL0904B and the Brazilian Ministry of Education. The first author would also like to thank for support by the Foundation fiat panis Ulm, Germany. The responsibility for the content of this publication lies with the authors.

3. *Spondias tuberosa* Arruda (Anacardiaceae), a Threatened Tree of the Brazilian Caatinga?

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Abstract

Spondias tuberosa Arr., a fructiferous tree endemic to the northeast Brazilian tropical dry forest called Caatinga, accounts for numerous benefits for its ecosystem as well as for the dwellers of the Caatinga. The tree serves as feed for pollinators and dispersers as well as fodder for domestic ruminants, and is a source of additional income for local smallholders and their families. Despite its vantages, it is facing several man-made and natural threats, and it is suspected that *S. tuberosa* could become extinct. Literature review suggests that *S. tuberosa* suffers a reduced regeneration leading to population decrease. At this juncture *S. tuberosa* cannot be considered threatened according to the International Union for Conservation of Nature Red List Categories and Criteria, as it has not yet been assessed and hampered generative regeneration is not considered in the IUCN assessment. The combination of threats, however, may have already caused an extinction debt for *S. tuberosa*. Due to the observed decline in tree density, a thorough assessment of the *S. tuberosa* population is recommended, as well as a threat assessment throughout the entire Caatinga.

Keywords: *Spondias tuberosa,* natural regeneration, conservation, IUCN red list, Caatinga.

Published in *Brazilian Journal of Biology*, ahead of print, 2016. The electronic version of this article is the definitive one, available at: http://dx.doi.org/10.1590/1519-6984.18715.

3.1 Introduction

The Red List of Threatened Species provided by the International Union for Conservation of Nature, (IUCN), is considered the most authoritative and objective system for categorizing the extinction risk of species (*Hambler and Canney*, 2013; *Hoffmann et al.*, 2008; *Rodrigues et al.*, 2006). IUCN structures the degree of risk of extinction of species into nine categories (*IUCN*, 2012). Eight of these nine categories are assigned only after an evaluation of species *in situ*. In case no evaluation took place species remain in the category “Not Evaluated” and in case data remain insufficient after evaluation species are assigned to “Data Deficient”. Species are evaluated against criteria with quantitative thresholds for geographic range and population size, structure and trends (*IUCN*, 2012) and if sufficient data are at hand assigned to one of the remaining seven categories ranging from “Least Concern” to “Extinct”. Species that meet the criteria for “Critically Endangered”, “Endangered” or “Vulnerable” are considered threatened (*IUCN*, 2012). An authoritative and objective system such as the IUCN red list is an important tool, beyond informing about the conservation of species, for identifying sites for conservation action on local as well as on regional level, to manage natural resources on national and international level, and to evaluate and monitor the state of global biodiversity (*Rodrigues et al.*, 2006).

Spondias tuberosa Arruda is an andromonoecious deciduous tree of the family Anacardiaceae, that is endemic to the Caatinga, a seasonally dry tropical forest (SDTF) of northeast Brazil (*Lima*, 1996; *Nadia et al.*, 2007; *Prado and Gibbs*, 1993). Its local name Umbuzeiro or Imbuzeiro is derived from the tupi-guarani indigenous word “ymb-u” which denotes “the tree that gives water” ((*Barreto and Castro*, 2010; *Epstein*, 1998)) in reference to a physiological adaption. *S. tuberosa* forms root tubers, which are able to store water, minerals, and organic solutes (*Cavalcanti et al.*, 2010; *Duque*, 2004; *Epstein*, 1998; *Lima*, 1996). This adaption permits its survival during the dry season (*Cavalcanti et al.*, 2010; *E. C. de Silva et al.*, 2008), and to initiate the flowering and leaf flush before onset of the rainy season (*Lima Filho*, 2007; *Machado et al.*, 1997). Due to these early signs of life in the otherwise dormant Caatinga at the end of the dry season, the tree is worshipped by indigenous tribes in spiritual rituals (*Monteiro*, 2007). Still today the majority of the Caatinga dwellers consider *S. tuberosa* a sacred tree (*Neto et al.*, 2010). The flowering of the entomophily and self-incompatible flowers in the late dry and the early rainy season makes it an important and unique food resource for pollinators as well as for nectar sucking animals (*Almeida et al.*, 2011; *Machado et al.*, 1997; *Nadia et al.*, 2007). Its fruits, the Brazilian plum, and leaves serve as fodder for small mammals as well as domestic sheep and goats (*Barreto and Castro*, 2010; *Cavalcanti et al.*, 2004a, 2009a; *Resende et al.*, 2004). In the human diet the fruit is consumed fresh or processed as juice, sweets, jam, ice cream, and umbuzada (fruit pulp boiled with milk and sugar) (*Narain et al.*, 1992; *Neto et al.*, 2010). Borges *et al.* (2007) state that during the fruit season, fruit picking and selling is a main source of earnings for the Caatinga dwellers, and can contribute significantly to household income (*Barreto and Castro*, 2010; *Drumond et al.*, 2001; *Reis et al.*, 2010). Fruit picking is virtually limited to extractivism as hardly any plantations have been established (*Narain et al.*, 1992; *Neves et al.*, 2004b; *Neves and Carvalho*, 2005) Moreover, *S. tuberosa* is used in traditional medicine and shows potential for its use in academic medicine (*Albuquerque et al.*, 2007; *Albuquerque and Oliveira*, 2007; *Almeida et al.*, 2010; *Júnior et al.*, 2011; *Neto et al.*, 2010; *Silva et al.*, 2011).

S. tuberosa occurs throughout the entire Caatinga biome, which covers approximately 845,000 km^2 (*IBGE*, 2004; *Lima*, 1996). Documented natural stand density ranges from 0.3 to up to 9 trees per hectare (see Table 3.1). Based on the publications below, the theoretical total population of *S. tuberosa* ranges from 21 million up to 630 million individuals within the Caatinga. Modeling *S. tuberosa* distribution within the Caatinga revealed that only 7 % of its population occur in existing conservation areas (*Ferreira*, 2014).

Regardless of the ecological, economic, and cultural benefits of *S. tuberosa*, concerns have been raised that the population of *S. tuberosa* is declining. In the early 1990s the Brazilian Corporation of Agricultural Research (Embrapa) pointed out that *S. tuberosa* may be in danger of extinction due to current agricultural land-use practices within the Caatinga (*Embrapa*, 1991). Albuquerque (1999) provided scientific backing for Embrapa's postulation by monitoring vegetation dynamics in a Caatinga area for six years under various grazing intensities. Although adult trees were present in the study area the researcher found neither seedlings nor saplings of *S. tuberosa*. In this study we focus and review international and national literature dealing with determining factors that pose a direct threat to the natural generative regeneration of *S. tuberosa*.

This may support decision makers to establish protection measures and conservation strategies for the emblematic species of the Caatinga.

Table 3.1: Stand density of *Spondias tuberosa* in the Caatinga according to different authors.

Stand density trees ha^{-1}	Author	Year of publication	State[1]
3.0	Albuquerque *et al.*	1982	PE
9.0	Drumond *et al.*	1982	PE
3.0	Albuquerque and Bandeira	1995	PE
0.9	Machado *et al.*	1997	PE
1.8 (1982)/ 2.8 (1984)	Albuquerque	1999	PE
Occur locally in anthropogenic zones	Albuquerque and Oliveira	2007	PE
7.6 undisturbed/ 3.4 disturbed Caatinga	Cavalcanti *et al.*	2008b	BA/PE
0.6	Albuquerque *et al.*	2011	PE
1.3 undisturbed/ 0.3 disturbed Caatinga	Bitterwolf	2014	PE

[1] Federal states: PE = Pernambuco, BA = Bahia

3.2 State of research

We searched Scopus (operated by Elsevier, Amsterdam) using the default search in the database and combined each of the search terms *Spondias tuberosa* Arr., *Spondias mombin* L., *Spondias purpurea* L., *Magnifera indica* L., and *Anacardium occidentale* L. with “in Article Title” or “in Abstract”. Despite the regional importance, only a limited number of scientific research work on

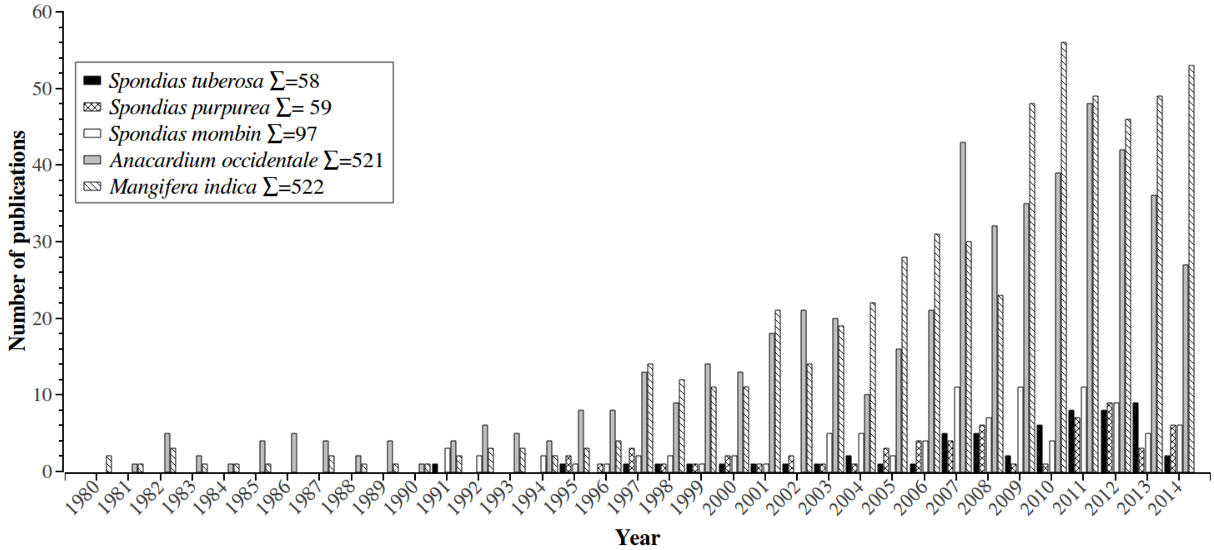

Figure 3.1: Publications of five Anacardiaceae per year according to Scopus database between 1980 and 2015. The query searched for the scientific name of the species in the article title or abstract.

S. tuberosa has been published. In comparison with other genera of the Anacardiaceae family most *Spondias* species seem to be under-researched (Figure 3.1). This can be partly explained by the wide distribution and economic importance of mango (*M. indica*) and cashew (*A. occidentale*). In the Brazilian context *S. mombin*, *S. purpurea* and *S. tuberosa* have, however, an equally high potential for agro-industrial exploitation (*Silva Junior et al.*, 2004; *Souza Almeida et al.*, 2007). Actually, in northeastern Brazil the profit of *S. tuberosa* fruit yield of 3.8 million USD in 2012 was almost double as high as that of *A. occidentale* (*IBGE*, 2013). In contrast, since 1980 almost tenfold more scientific journal articles on *A. occidentale* have been published than on *S. tuberosa* according to Scopus (Figure 3.1). Expanding the search to include the ScienceDirect, Google Scholar, and SciElo databases, a total of about 100 articles focusing on *S. tuberosa* were published within the same time frame. Of these articles about 40 % are available only in Portuguese language with an English abstract. In nine of all 100 reviewed publications on *S. tuberosa* concerns about weak natural regeneration were directly or indirectly raised, but only five actually investigated underlying reasons and causes. The need to investigate the population dynamics of *S. tuberosa* to identify potential threats and protective measures is, however, well recognized. Since at least eight on-line magazine articles and blog entries broach the issue of the reduction in *S. tuberosa* density and hampered natural regeneration (*Bartaburu*, 2013; *Cavalcanti*, 2013, 2007; *Cavalcanti and Resende*, 2005; *ECOD*, 2013; *IRPAA*, n.d.; *Moser*, 2013).

3.3 Factors reported constraining the natural regeneration of *Spondias tuberosa*

Several constraints are known to hamper the natural generative regeneration in plants. These constraints could be abiotic, such as shade, excess light, heat, water stress, and flooding, or biotic, such as allelopathy, browsing, herbivores, seed predation, and soil-borne pathogens (*Guariguata and Pinard*, 1998; *Harmer*, 2001; *Harrington and Bluhm*, 2001; *Kitajima and Fenner*, 2000; *McLaren and McDonald*, 2003; *Torres et al.*, 2008). Further, anthropogenic constraints such as land-use, fuel-wood and timber extraction as well as the extraction of non-timber products are also known to negatively impact natural generative regeneration (*Avocèvou-Ayisso et al.*, 2009; *Bhuyan et al.*, 2003; *Lykke*, 1998; *Pare et al.*, 2009; *Ræbild et al.*, 2007; *Schumann et al.*, 2011). Studies provide evidence that when multiple biotic and abiotic constraints are present, the negative effects on regeneration from seeds can be amplified (*Gutiérrez-Granados et al.*, 2011). Detailed constraints as reported in the literature that may interfere with the natural regeneration of *S. tuberosa* are summarized below.

Pests

98 % of seeds from fallen fruits of *S. tuberosa* have been reported to be infested by the grubs from the seed beetle *Amblycerus dispar* Sharp, thereby the harmed embryo is unable to germinate (*Cavalcanti et al.*, 2008a, 2009a; *Cavalcanti and Resende*, 2004). Whereas fruits collected directly from the tree did not show any infestation. Since the seeds collected from the tree were stored for 30 days before being checked for infestation, Cavalcanti and Resende (2004) assume the infestation takes place on the seed rain before dispersal and not on the tree. Bitterwolf (2014) observed an infestation rate of 100 % of seeds collected in 1 m^2 plots underneath the canopy of 25 trees during his field survey. The author only collected seeds from the ground, which was not cleared before the fruit season, and therefore was not possible to know the timing and location of infestation. It is not known whether the infestation of *A. dispar* increased recently and became a new problem for the *S. tuberosa* regeneration. Besides the seed beetle affecting germination rate, other insects are reported to harm *S. tuberosa* during the critical seedling stage and continue to affect the survival of seedlings (*Cavalcanti et al.*, 2006a). The insects known to damage *S. tuberosa* seedlings are *Phasmatodea* spp., *Diabrotica specosa* Germar, *Megalopyge lanata* Stoll, *Cryptotermes* spp., *Pinnaspis* spp. (*Neves and Carvalho*, 2005). Further, two pathogenic fungi are associated with *S. tuberosa*, *Colletotrichum gloeosporioides* (Penz.) Penz and Sacc., and *Guignardia* spp. (*Freire and Bezerra*, 2001; *Tavares et al.*, 1998). Detailed studies on the nature and degree of *S. tuberosa* damage caused by these insects and fungi are still lacking.

Restricted seed dispersal

The dispersal of *S. tuberosa* seeds occurs exclusively through zoochory. Seeds are carried by native animals, such as gray brocket (*Mazama gouazoubira* Fische), black-rumped agouti (*Dasyprocta prymnolopha* Wagler), collared peccary (*Pecari tajacu* Linnaeus), fox (*Dusicyon thous* Linnaeus), yellow armadillo (*Euphractus sexcinctus* Linnaeus), argentine black and white tegu (*Tupinambis merianae* Linnaeus), greater rhea (*Rhea americana* Linnaeus) and white-naped jay (*Cyanocorax cyanopogon*, Wied-Neuwied) (*Azevedo et al.*, 2013; *Barreto and Castro*, 2010; *Cavalcanti et al.*, 2009a; *Cavalcanti and Resende*, 2003). The non-native, human introduced cattle (*Bos taurus* Linnaeus) and goat (*Capra aegagrus hircus* Linnaeus) are also reported dispersing seeds of *S. tuberosa* (*Barreto and Castro*, 2010; *Griz and Machado*, 2001).

Among the mentioned natural dispersers *M. gouazoubira* and *P. tajacu* are the most important (*Cavalcanti et al.*, 2009a). While both species were formerly omnipresent in the biome, today they are found only in a few municipalities (*Oliveira et al.*, 2003), which indicates a process of severe population reduction of these dispersers within the Caatinga. Cavalcanti *et al.* (2009b) suppose that is due to severe pressure from hunting. Thus, the results of Cavalcanti *et al.* (2009a) suggest that the dispersal of *S. tuberosa* in areas of undisturbed Caatinga is restricted due to the lack of natural dispersers. In addition *E. sexcinctus* is experiencing severe hunting pressure as well (*Alves et al.*, 2009). As stated in Alves *et al*. (2009) wild animals have still a great nutritional importance for low-income families in the Caatinga, consequently hunting remains a common activity despite its illegality in regions of extreme poverty. Therefore Barreto and Castro (2007) recommended a reduction of hunting wild animals within the Caatinga as a protection measure for the wild population of *S. tuberosa*. This can be only achieved by better law enforcement in order to stop commercial hunting as well as for non-food purposes (*Alves et al.*, 2009).

According to the cited literature the restricted seed dispersal is one of the key reasons for low natural regeneration of *S. tuberosa* in the Caatinga.

Climate change

The area which comprises today's Caatinga underwent a natural climatic change. Based on analysis of pollen in a peat bog sequence Oliveira *et al.* (1999) identified a humid period from 10,990 – 8,910 yr B.P. with pollen from taxa which occur in the present day Amazonian and Atlantic forests. From 8,910 yr B.P. onwards the climate got drier as indicated by increasing density of pollen from SDTF vegetation. Acceleration in this shift towards a more semiarid climate was observed from 4,240 yr B.P. until present, which lead to the dominance of SDTF vegetation (*Oliveira et al.*, 1999). This historical trend towards a drier environment in the Caatinga may continue due to man-made climate change. The Intergovernmental Panel on Climate Change (*IPCC*, 2007a) stated: that due to increased atmospheric concentrations of greenhouse gases, extreme weather events such as extreme droughts, intensification of hot extremes and heat waves have increased in frequency and severity and are more likely in the future. Most likely the semiarid Brazilian Northeast will suffer a decrease of water resources due to climate change and the semiarid vegetation will tend to be replaced by arid-land vegetation (*IPCC*, 2007b). This may also affect the survival, natural regeneration, and persistence of *S. tuberosa* in the current extension of the Caatinga biome. Higher temperatures will also accelerate drought-induced tree mortality (*Adams et al.*, 2009). In addition, droughts and dry conditions within SDTF reduce seed germination and increase seedling mortality (*Blain and Kellman*, 1991; *McLaren and McDonald*, 2003). For *S. tuberosa* in particular Cavalcanti *et al.* (2006a) observed reduced germination and seedling survival in months with little or no precipitation. Lima *et al.* (2015) observed a little seedling survival of planted *S. tuberosa* seedlings, due to under-average precipitation during the experiment the authors stated. Recurring dry years took place in the Caatinga throughout the entire 19th Century (*Untied*, 2005), but Silva (2004) observed a trend towards a drier climate in the Brazilian Northeast within the most recent 30 years. The ongoing environmental degradation may even intensify this trend within the Caatinga as modeled by Oyama and Nobre (2004). Based on precipitation data available at Agência Pernambucana de Águas e Clima (*APAC*, 2015) the trend observed by Silva (*Silva*, 2004) could be supported for the Caatinga in Pernambuco (PE). At four of six weather stations, the least-squares linear regression indicates a slightly decreasing trend in annual precipitation over the last 75 years (see Annex Figure 9.1).

Besides germination and seedling survival the fruit set of *S. tuberosa* is also affected by the soil water regime. Cavalcanti *et al.* (2011) demonstrated the positive effect of additional irrigation on bloom and fruit set, thus decreasing precipitation may lead to reduced fructification of *S. tuberosa*. Precipitation in the beginning of the rainy season from November to December is especially important for the development of fruits (*Cavalcanti et al.*, 2011). Therefore, natural generative regeneration of *S. tuberosa* may be impeded by reduced seed germination and seedling mortality on the one hand, and on the other hand due to reduced fructification.

Browsing

Browsing by *C. hircus*, the domestic goat, impacts the natural generative regeneration of *S. tuberosa* in two ways. First, Caatinga sites disturbed by grazing, and browsing, show a strong decline in number of *S. tuberosa* seeds, 1004 seeds m^{-2} on undisturbed Caatinga sites versus 31 seeds m^{-2} on disturbed Caatinga sites (*Cavalcanti et al.*, 2009a). The authors argue that the decline in number of seeds is caused by *C. hircus* as they feed on fruits of *S. tuberosa* and export the seeds out of Caatinga sites into a night-time enclosure. An individual goat can take up over 130 kg of Brazilian plum during one fruit season from January until April which represents an export of approximately 10,000 fruits (*Resende et al.*, 2004). Second, *C. hircus* also feed on seedlings and saplings of *S. tuberosa*. On disturbed Caatinga sites 62 % of 1000 planted *S. tuberosa* seedlings were marred by *C. hircus*, which reduced the seedling survival to 22 % within three consecutive years (*Cavalcanti et al.*, 2009b). Cavalcanti *et al.* (2009a) did not find any seedling of *S. tuberosa* on Caatinga sites with evidence of *C. hircus* browsing impact. As *C. hircus* impedes dispersal, and damages seedlings, it hinders the natural generative regeneration and causes the disappearance of *S. tuberosa* in disturbed Caatinga sites (*Cavalcanti et al.*, 2009a, 2009b). Furthermore, it has been reported that sheep (*Ovis gmelini aries* Linnaeus) significantly feeds on Brazilian plum (*Martinele et al.*, 2010; *Resende et al.*, 2004). Recently, Siqueira Filho (2012) expressed concerns about browsing pressure which may affect the natural regeneration of *S. tuberosa*.

On undisturbed Caatinga sites, the dispersers of *S. tuberosa*, *P. tajacu* and *E. sexcinctus* affect *S. tuberosa* seedlings negatively by browsing as well (*Cavalcanti et al.*, 2009b, 2006a). On an undisturbed Caatinga site 14 % of 1000 planted seedlings of *S. tuberosa* were damaged by *E. sexcinctus* and 7 % were damaged by *T. tajacu* (*Cavalcanti et al.*, 2009b). The damage on *S. tuberosa* seedlings caused by *E. sexcinctus* is especially severe, since it excavates and feeds on the root tubers which kills the seedling (*Cavalcanti et al.*, 2009b, 2006a). Since *P. tajacu* and *E. sexcinctus* interfere with the dispersal of *S. tuberosa* due to their absence, we assume the browsing impact of both is rather insignificant.

3.4 Potential factors which may constrain the natural regeneration of *Spondias tuberosa*

Two further anthropogenic factors, wood extraction and fruit picking, may also account for hampered natural generative regeneration of *S. tuberosa.* Even though both factors are not referenced in *S. tuberosa* literature to date.

Wood extraction

Despite a draft law filed in 2004, which would ban lumbering of *S. tuberosa* (*Projeto de Lei No 3.548, DE 2004 - Dispõe sobre a proibição da derrubada do umbuzeiro em todo país, e dá outras providências.*, 2004), it has been reported that *S. tuberosa* wood is still used as fuelwood or used for charcoal production (*Neto et al.*, 2010; *Sá e Silva et al.*, 2009). Wood extraction accounts for reduced natural generative regeneration as shown by Bhuyan *et al*. (2003) in an Indian tropical forest. They observed decreasing regeneration with increasing human-impact, and in highly disturbed sites no regeneration was recorded. However, Jurisch *et al*. (2013) observed a positive effect of human disturbance on the seedling survival in an African savanna due to reduced competition for light, water, and nutrients. At this point, neither the status of the draft law is known nor the extent and effect of wood extraction on *S. tuberosa*.

Fruit picking

Fruit picking must also be considered a potential constraint for natural generative regeneration of *S. tuberosa*. In 2012 the yield of the Brazilian plum, 7979 t, was harvested by fruit picking from naturally occurring *S. tuberosa* (*IBGE*, 2013). It can be assumed, that harvesting is much higher, since a significant amount of Brazilian plum is consumed directly within rural communities or sold via farm gate or at roadside (*Barreto and Castro*, 2010; *Neto et al.*, 2010) which is not recorded by the official survey. Hence, fruit picking may reduce the seed rain of *S. tuberosa* and reduction of the natural generative regeneration is a consequence. For instance, Avocèvou-Ayisso *et al.* (2009) observed a decline in total seedlings and saplings of African butter tree (*Pentadesma butyracea* Sabine), a multipurpose tree

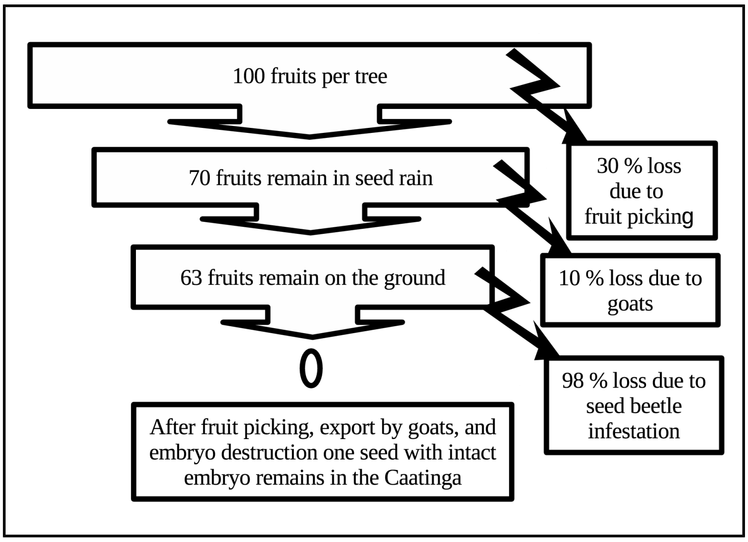

Figure 3.2: Assumed reduction of germinable seeds of *Spondias tuberosa* due to fruit picking, seed export of goats and seed beetle infestation within Caatinga.

in the African tropical forest, as well as reduced generative regeneration due to high fruit harvesting intensity. Yet, the impact of fruit extractivism on *S. tuberosa* needs to be further investigated, reaching reliable data on fruits exported out of the Caatinga.

3.5 Conclusion

This review highlights the various constraints of natural generative regeneration *S. tuberosa* is exposed. Since the reported constraints are successively combined and maybe even amplify themselves the natural regeneration of *S. tuberosa* appears severely disturbed. For instance, logging amplified seed predation and storm disturbance facilitated herbivore attacks on seedlings of big-leaf mahogany (*Swietenia macrophylla* King) (*Gutiérrez-Granados et al.*, 2011). A trend towards a drier climate in the Brazilian Northeast may reduce the fructification of *S. tuberosa*. Additionally, the popularity of animal husbandry as well as fruit picking results in an export of its fruits and seeds out of the Caatinga, which reduces the share of *S. tuberosa* seeds within the seed pool of the Caatinga. The significantly reduced number of seeds of *S. tuberosa* remaining on Caatinga sites is exposed to the risk of seed predation by the seed beetle *A. dispar* and the number of germinable seeds is drastically reduced (Figure 3.2). According to Guariguata and Pinard (1998) seed predation is a major constraint for tree regeneration in neotropical forests. Due to the decreased abundance of natural dispersers the remaining seeds with intact embryos will not be dispersed appropriately and the formation of new populations is very unlikely. With little and erratic precipitation, intact seeds have difficulties meeting favorable environmental conditions for their germination. If the trend in decreasing precipitation proves true, meeting these favorable conditions will be even more difficult. Thus, *S. tuberosa* is potentially affected twice by climate change; a drier environment will reduce fructification and hamper germination. In case germination takes place and the seedling emerges, *S. tuberosa* needs to pass another bottleneck in its generative regeneration, the seedling stages. In this stage, *S. tuberosa* is exposed to high browsing pressure on disturbed Caatinga sites. In the seedling stage the natural regeneration of trees is especially sensitive to browsing (*Côté et al.*, 2004; *Gill*, 1992; *Harmer*, 2001). Both, the abundance of browsers and the abundance of seedlings affects the success of the natural regeneration (*Gill*, 1992). Accordingly, the reported browsing of *C. hircus* has a stronger impact on the natural regeneration, as the number of seedlings of *S. tuberosa* is reduced due to a reduced share in the seed pool, hampered dispersal and germination constraints compared to a situation without reduced seedling abundance. As seen for the trend towards a drier climate, *C. hircus* interferes twice with the natural regeneration of *S. tuberosa* as well. This multifactorial disturbance of the natural regeneration may cause a serious extinction debt for *S. tuberosa*.

Although strong evidence support the fear of a hampered generative regeneration of *S. tuberosa*, it cannot be considered threatened according to IUCN criteria at this juncture. *S. tuberosa* has not yet been evaluated and a hampered generative regeneration is not considered in the ICUN assessment. It maintains the status of “Not Evaluated” in IUCN red list (*IUCN*, 2016, 2012). In case of *S. tuberosa*, neglecting the generative regeneration in the assessment of IUCN might be irrelevant, since it is assumed that the regeneration via re-sprouting after disturbance is of greater importance than generative regeneration in SDTFs (*Vieira and Scariot*, 2006). There is currently no literature about whether the hampered generative regeneration *de facto* affects the *S. tuberosa* population. So far only concerns were stated. However, knowledge regarding factors which constrain the regeneration of *S. tuberosa* is still partly lacking or rudimentary (Table 3.2), which highlights the need for further research. Additionally, the population density and the strong variation in the population density over time should be investigated closely, especially in other regions of the Caatinga. All publication which assessed the tree density of *S. tuberosa* were carried out almost exclusively in the state Pernambuco (Table 3.1).

We suggest a large-scale thorough assessment of the *S. tuberosa* population in the Caatinga with focus on an allometric and age structure assessment as well as its spatial distribution. Ideally, a comparison with historical data should be included in order to obtain information about temporal alteration. The early bloom of *S. tuberosa* in the otherwise dormant Caatinga may result in distinctive spectral and textural signals, and remote sensing could a promising tool for a large-scale assessment. Such an approach, when proven applicable and incorporated into a geographical information system (GIS), could be used to evaluate the status of *S. tuberosa* for the IUCN red list, and as a basis for future assessments of spatial and temporal population dynamics, triggered by climate change for instance. The remote sensing also may help to identify areas with high protection value for *S. tuberosa*. It also must be verified whether the impeding biotic and abiotic factors described above apply to the entire Caatinga and to which extent these factors affect *S. tuberosa*. Therefore, we recommend additionally the installation of surveillance plots within the Caatinga for ground-based assessment, in which the damaged caused by insects and fungi on *S. tuberosa* as well as the effect of climate change on germination, seedling survival, bloom, and fruit set of *S. tuberosa* could be observed.

Table 3.2: Selected factors influencing the natural regeneration of *Spondias tuberosa*, their potential damage and state of knowledge.

Threat	Potential damage[2]	State of knowledge[3]
Seed predation by beetle	+++	+
Herbivore insects	+	-
Restricted natural dispersal	++	0
Drier climate	+++	0
Browsing pressure	+++	+
Wood extraction	++	-
Fruit picking	++	-

[2]: + = little potential damage, ++ = intermediate potential damage, +++ = high potential damage. [3]: - = little or no knowledge, 0 = basic knowledge, + = good knowledge.

Acknowledgements

This work was supported by the German-Brazilian joint research project INNOVATE (Interplay between the multiple uses of water reservoirs via innovative coupling of substance cycles in aquatic and terrestrial ecosystems). The project is funded by the German Federal Ministry of Education and Research (BMBF) under project number 01LL0904B. The first author would also like to thank for support by the Foundation fiat panis Ulm, Germany.

4. Effect of Biochar, Clay Substrate, and Manure Application on Water Availability and Tree-Seedling Performance in a sandy Soil

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Abstract

In order to develop a method for extensive pomiculture on marginal soils in semiarid Brazil, a field experiment was conducted to study the impacts of the soil conditioners biochar, clay substrate, and goat manure on soil physical parameters of a sandy soil and on seedling performance of *Spondias tuberosa* Arruda.

Manure significantly increased total porosity, soil water content, and reduced bulk density of the sandy soil. Water content at field capacity (θ_{fc}) and at permanent wilting point (θ_{pwp}) were increased due to manure application. Neither biochar nor clay substrate had a significant impact on the soil physical parameters. Biochar combined with clay substrate led to lower soil water content and significantly reduced the period of retaining atmospheric water. Due to a strong correlation (R^2 = 0.75) between θ_{fc} and θ_{pwp} the available water capacity within all treatments remained unchanged.

Amelioration and initial nutrient supplies had no effect on seedling survival and stem growth of *S. tuberosa* during the 23-months experiment. This underlines the nondomesticated character of the available plant material of *S. tuberosa*. The independence of the seedling performance of soil management makes *S. tuberosa* an interesting species for low-input orchards and for reforestation within the Caatinga.

Keywords: Arenosol, ameliorant, soil amendment, seedling performance, Umbuzeiro.

Published in *Archives of Agronomy and Soil Science*, 63, 969–983, 2017. The electronic version of this article is the definitive one, available at: http://dx.doi.org/10.1080/03650340.2016.1249473. With kind permission of Taylor & Francis.

4.1 Introduction

The Brazilian Northeast is dominated by a deciduous thorny woodland vegetation called Caatinga, which extends over an area of approximately 845,000 km^2, about 9.9 % of total Brazilian territory (*IBGE*, 2004). This ecoregion belongs to the seasonally dry tropical forests with little and erratic precipitation ranging from 240 to 900 mm $year^{-1}$ usually concentrated during the southern hemisphere summer from November until June (*Prado*, 2003). The highly diverse and endemic Caatinga vegetation faces severe anthropogenic pressure due to agricultural land-use, animal husbandry, fuel wood extraction and man-made fire, which facilitates habitat degradation and leads to desertification (*Leal et al.*, 2005). Prevailing agricultural land-use within the Caatinga is divided into intensive modern export-oriented irrigation farming and irrigated or rain-fed subsistence farming (*Untied*, 2005). However, soils adequate for irrigation are limited and surface water resources are restricted to the catchment area of São Francisco river (*Araújo Filho*, 2011; *Untied*, 2005). As an income alternative for smallholders outside of irrigation projects, animal husbandry is common. The biggest herd of domestic goat (*Capra hircus* Linnaeus) in Brazil is located within the Caatinga, which has a severe impact on native vegetation (*Leal et al.*, 2003). To lower the grazing pressure on the Caatinga vegetation the fructiferous endemic tree *Spondias tuberosa* Arr., locally known as Umbuzeiro, might provide an additional revenue for smallholders. Currently, yields of *S. tuberosa* are limited to extractivism. So far managed plantations as well as scientifically backed cropping systems for *S. tuberosa* are still lacking. Climate factors, shallow and stony soils, and the poor water retention capacity of deep soils (Arenosols) are the main limiting factors for farming in the Caatinga (*Araújo Filho*, 2011). The poor water retention capacity of the Arenosol is attributed to their little content of the fine particles' silt and clay (< 0.02 mm) (*Araújo Filho et al.*, 2013). The application of biochar, clay, and manure can improve soil physical or rather soil hydraulic properties of sandy soils (*Abel et al.*, 2013; *Asghari et al.*, 2009; *Basso et al.*, 2013; *Ismail and Ozawa*, 2007; *Mojid et al.*, 2012).

The aim of this work was (1) to evaluate physical parameters of a sandy soil after soil amelioration with biochar, clay substrate, goat manure, and their combinations under semiarid field conditions and (2) to assess the new cultivation technique on *S. tuberosa* growth and development.

4.2 Material and methods

Site description

The study site was located in the Petrolândia municipality of Pernambuco in northeastern Brazil (S8°57'24.1'', W38°15'00.4'', 330 m a.s.l.). The prevailing climate is hot semiarid, classified as BSh according to Köppen-Geiger, with an annual mean temperature of 24.3°C and an annual precipitation of 438 mm (1982 – 2012). The degraded site, four ha in size, was fenced to avoid further grazing and browsing in January 2013. During the experiment (June 2013 – June 2015), an annual mean temperature of 26.6°C and an average annual precipitation of 254 mm were recorded on-site.

Experimental design

The one-factorial field experiment contained 13 treatments with ten replicates. The treatments differed in the backfill mix for the cylindric planting holes (h = 55 cm; r = 30 cm). Soil conditioners used for the backfill mix were goat manure (40 % v/v), clay substrate (10 % v/v), biochar (5 % v/v). Each conditioner was applied sole as well as in combination, along with topsoil as required (Table 4.1). A total of 130 planting locations were selected within the patchy Caatinga vegetation with a minimum distance to the surrounding vegetation of 1.5 m. The locations were consecutively numbered and for each numbered location, one replicate was randomly assigned. Planting holes and backfill mixes were prepared according to the assigned treatment for each location. The experimental design contained two control treatments. Control 1 was an undisturbed soil treatment preparation where no planting hole exceeded the root ball width. Control 2 used the spacious planting hole specified above, but without any soil amendments or mineral fertilizer in the backfill mix. The soil conditioners were manually mixed with the excavated topsoil prior to refilling the planting holes. Twelve weeks after refilling, seedlings of *S. tuberosa* were planted in the center of each planting hole. Sixteen days after planting, a basal dose of mineral fertilizer was applied to the respective treatments. Nitrogen (urea), phosphorus (simple super phosphate) and potassium (KCl) were applied to achieve at least the recommended concenstrations within the planting hole after Neves *et al.* (2008b, 2007a, 2007b): 0.4 mg N g^{-1}, 0.2 mg P g^{-1}, 0.4 mg K g^{-1}. Seedlings were irrigated with 2 liters of water per week until February 2015.

Plant material

Non-grafted one-year-old *S. tuberosa* seedlings were made available by Embrapa Semiárido, Petrolina, Pernambuco, Brazil (Embrapa-CPATSA). To obtain a reasonable homogeneous plant material, all seeds originated from the same mother tree.

Soil analyses

Random soil samples (0 – 20 cm depth) were taken using a riverside auger at 10 locations before installation of the experiment. Out of the pooled sample, subsamples were taken for chemical analysis and particle size distribution analysis. The soil type was determined at a 160 cm deep profile pit on-site. Particle size distribution and pH in H_2O were measured according to ("DIN / ISO 11277: Soil quality - Determination of particle size distribution in mineral soil material - Method by sieving and sedimentation," 2002) and ("DIN / ISO 10390: Soil quality - Determination of pH," 2005). Carbon (C) and total nitrogen (TN) content were analyzed with gas chromatography (vario EL III, Elementar Analysensysteme GmbH, Hanau, Germany) and plant available phosphorus (P^{CAL}) and available potassium (K^{CAL}) were measured with inductively coupled plasma optical emission spectrometry (ICP-OES) (iCAP 6000 ICP Spectrometer, Thermo Fisher Scientific, Dreieich, Germany) in a 0.05 mol calcium-acetate-lactate (CAL) extract.

The soil was classified as Arenosol (*IUSS Working Group WRB*, 2014) containing 95.3 % sand, 0.4 % silt, and 4.3 % clay with a pH of 5.1. It contained 1.62 mg C g^{-1}, 0.22 mg TN g^{-1}, 0.05 mg P^{CAL} g^{-1}, and 0.19 mg K^{CAL} g^{-1}.

Sixteen months after the planting holes had been refilled, additional soil samples were taken with a Pürckhauer auger from the single soil conditioner treatments Manure, Clay, and Biochar as well as from Con1, and Con2 treatment (0 – 55 cm), in order to estimate the soil carbon stability under given conditions. The loss of C stock in percentage, calculated by initial C content and C content after 16 months, was used as an indicator for soil carbon stability in these five treatments. The C content of these soil samples was measured with the gas chromatograph mentioned above.

Soil conditioners

Samples of all soil conditioners were subjected to analysis before the experiment using the same techniques as described for soil chemical and soil physical analysis. The TN content of goat manure was not determined with the mentioned gas chromatography but according to Kjeldahl (1883). In order to determine the water repellency of the utilized biochar the water drop penetration time (WDPT) test (*Dekker et al.*, 2009) was conducted on a retained sample. Three droplets of distilled water were placed onto the surface of three 5 g subsamples of biochar with a 20 ml graduated pipette and the time for their complete infiltration was recorded.

The biochar utilized in the experiment was produced by a local charburner using a burrow sealed with a corrugated sheet and clay as a charcoal kiln. Pyrolysis temperature as well as the residence time of the feedstock was not recorded. Feedstock was *Prosopis juliflora* (Sw) DC and the product was crushed using a knife mill and sieved to a particle size < 5 mm. The biochar C content was 969 mg C g^{-1} with 3.70 mg TN g^{-1}, 0.07 mg P^{CAL} g^{-1}, 1.06 mg K^{CAL} g^{-1} and a pH of 9.1.

Mudstone is the parental material of the clay substrate collected from the bottom of a parched lake near the city of Petrolândia (S8°57'50.6'' W38°10'42.1'', 318 m a.s.l.). It consisted of 30.2 % silt and 69.8 % clay. The clay fraction comprised 40 – 60 % smectite, 10 – 30 % illite, 20 – 30 % kaolinite, and < 10 % Fe-oxides, calcium carbonate, and organic materials (*personal communication with JC de Araújo Filho*, 2012). The clay substrate contained 17 mg C g^{-1}, 0.70 mg TN g^{-1}, 0.14 mg P^{CAL} g^{-1}, and 2.94 mg K^{CAL} g^{-1}. Air-dry moisture content was 2 vol.% and pH was 7.7.

Goat manure originated from a night enclosure for domestic goats in the irrigation project Manga de Baixo (S 8°44'39.0'' W 38°51'29.4'', 313 m a.s.l.). C content was 854 mg C g^{-1} and contained 0.16 mg TN g^{-1}, 0.54 mg P^{CAL} g^{-1}, and 2.60 mg K^{CAL} g^{-1}. Air-dry moisture content was 6.4 vol.% and pH was 7.1.

Table 4.1: Control and treatments with their corresponding abbreviations, the volumetric proportion of backfill materials and initial soil chemical parameters of the backfill mix. Recommended nutrient concentration according to Neves *et al.* (2008a, 2007a, 2007b).

Control/ Treatment	Abbreviation	Topsoil %	Goat manure %	Clay substrate %	Biochar %	N mg g^{-1}	P mg g^{-1}	K mg g^{-1}	TC mg g^{-1}*
Control 1 undisturbed soil	Con1	100	–	–	–	0.20	0.05	0.19	1.60
Control 2 disturbed soil	Con2	100	–	–	–	0.20	0.05	0.19	1.60
Mineral fertilizer	MinFert	100	–	–	–	0.41	0.24	0.35	1.60
Biochar	Biochar	95	–	–	5	0.19	0.05	0.18	14.99
Biochar + Mineral fertilizer	BioMin	95	–	–	5	0.41	0.24	0.35	14.99
Clay substrate	Clay	90	–	10	–	0.18	0.05	0.17	2.91
Clay substrate+ Mineral fertilizer	ClayMin	90	–	10	–	0.41	0.24	0.35	2.91
Clay substrate+ Biochar	ClayBio	85	–	10	5	0.17	0.05	0.17	16.59
Clay substrate+ Biochar + Mineral fertilizer	ClBioMi	85	–	10	5	0.41	0.24	0.35	16.59
Goat manure	Manure	60	40	–	–	0.47	0.04	0.17	156.58
Goat manure + Mineral fertilizer	ManMin	60	40	–	–	0.47	0.24	0.35	156.58
Biochar + Goat manure	BioMan	55	40	–	5	0.50	0.04	0.09	183.23
Biochar + Goat manure + Mineral fertilizer	BiMaMi	55	40	–	5	0.50	0.24	0.35	183.23

*** before Urea application.**

Soil physical analyses

The volumetric soil water content within the planting hole was measured with a frequency domain reflectometry (FDR) soil probe (PR2 by Delta-T Devices Ltd., Cambridge, UK) once a week from 1st of June 2013 until 31st January 2015 between 6:00 AM and 8:00 AM.

To assess the ability of the modified planting holes to retain atmospheric water over time during the rainy season, irrigation was halted from February 2015 onward. After a rain event of March 1st 2015 (10.4 mm), FDR measurements took place every 6 h for the first 12 h, every 24 h for the next 96 h, then after 27 h, and then every 96 h. The series of measurements was maintained for 480 h until March 22nd, when a further rain event took place.

Infiltration into the planting hole was estimated via field-saturated soil hydraulic conductivity (K_{fs}) in April 2015 using the simplified Beerkan infiltration test (*Bagarello et al.*, 2014). The cylinder used had a 150 mm radius and $\alpha^* = 0.036$ mm s^{-1} was defined. The α^*, the ratio between K_{fs} and the field-saturated matric flux potential, was evaluated for coarse-textured soils according to Elrick and Reynolds (1992).

Following the infiltration test undisturbed soil samples were taken with 100 cm^3 sampling rings in each planting hole at 20 cm, 40 cm, and below the planting hole at 80 cm soil depth to determine bulk density (ρ_b), total porosity (Φ), water content at field capacity (θ_{fc}), and water content at permanent wilting point (θ_{pwp}) according to Embrapa guidelines (*Donagema et al.*, 2011). The θ_{fc} and θ_{pwp} were each measured at -0.033 MPa and at -1.5 MPa with a ceramic plate extractor. Available water capacity (θ_a) and air capacity (AC) was calculated as follows:

$$\theta_a = \theta_{fc} - \theta_{pwp} \quad (1)$$

$$AC = \Phi - \theta_{fc} \quad (2)$$

Φ was calculated by the use of particle density (ρ_p), determined by submerging a 20 g subsample of oven dried soil in ethanol in a 50 ml volumetric flask, and ρ_b:

$$\Phi = \left(\frac{\rho_p - \rho_b}{\rho_p}\right) \times 100 \quad (3)$$

The chosen suction of -0.033 MPa for θ_{fc} slightly underestimates the θ_{fc} of the untreated Arenosol of this experiment (*Ruiz et al.*, 2003), but allows interrelating the θ_{pwp}, θ_a, and AC with different soil pore classes. Accordingly, the AC represents the macroporosity (> 50 – 10 µm), θ_a the mesoporosity (10 – 0.2 µm), and θ_{pwp} the microporosity (< 0.2 µm) of the substrates (*Luxmoore*, 1981).

Plant analyses

Treatment effects on plant growth were assessed nondestructively by recording stem circumference. The stem circumference was measured at ground level at 3 cm (*Sampaio and*

Silva, 2005). It was recorded in May 2013, 2014, and 2015. During the 2013/2014 and 2014/2015 rainy season, the dieback of the seedlings was recorded bi-monthly.

Statistics

For data analysis, four replicates of each treatment were randomly selected. Soil physical and plant growth data were tested for normality of residues and homoscedasticity. Treatment effects on all measured parameters were tested with a one-way ANOVA. Bulk density, infiltration, and growth rate of stem circumference data were transformed with the decadic logarithm before subjected to ANOVA. For pairwise comparison of means, the Tukey HSD test with $\alpha = 0.05$ was performed. The dieback of the seedlings was analyzed with Kaplan-Meier estimator that computed a survival probability between 1 and 0 per treatment during the 23 months after planting. The resulting survival functions, which map the dieback of seedlings per treatment onto time, were compared between treatments with a log-rank test. All statistical analyses were conducted with R expanded with the agricolae, ggplot2, and survival packages (*Mendiburu*, 2014; *R Core Team*, 2016; *Therneau*, 2015; *Wickham*, 2009).

4.3 Results

Bulk density (ρ_b), total porosity(Φ) and air capacity (AC)

Bulk density (ρ_b) and Φ were significantly different between treatments at 20 cm and 40 cm soil depth. At 80 cm soil depth, no treatment effect was reported (Table 4.2). At 20 cm soil depth, Manure significantly decreased ρ_b as well as significantly increased Φ compared to both control treatments. Moreover, BiMaMi and BioMan significantly decreased ρ_b compared to both control treatments and the Φ significantly decreased in BiMaMi compared to Con1. At 40 cm for BiMaMi and ManMin, ρ_b significantly decreased compared to Con1 and BiMaMi significantly increased Φ compared to Con1. Neither biochar nor a clay substrate addition significantly changed ρb or Φ at 20 cm, and 40 cm soil depth (Table 4.2).

The AC only showed significant difference between treatments at 20 cm soil depth ($p = 0.009$). The AC of Manure, 40.3 %, was significantly higher than the AC of ClBioMi, 35.1 % according to the Tukey test.

Although the goat manure addition did not lead to differences in ρ_b, Φ, and AC at different soil depths within the planting holes, compared with the untreated soil at 80 cm soil depth, the goat manure addition significantly reduced ρ_b and significantly increased Φ within the planting holes. (data not shown).

Water content at field capacity (θ_{fc}), water content at permanent wilting point (θ_{pwp}) and available water capacity (θ_a)

At 20 cm and 40 cm soil depth, θ_{fc} as well as θ_{pwp} were significantly different between treatments (Table 4.3). At 80 cm soil depth, no treatment effects on θ_{fc} or θ_{pwp} were observed. ClBioMi significantly increased θ_{fc} compared with both control treatments at 20 cm. Even though the ANOVA identified significant effect of treatments at 40 cm, no significantly different groups for θ_{fc} were indicated. At 20 cm, BiMaMi, ClBioMi, and Manure significantly increased θ_{pwp} compared with the control treatments. At 40 cm, BiMaMi, ManMin, and Manure significantly increased θ_{pwp} compared to the control treatments.

Table 4.2: ANOVA *p*-values, mean values and standard deviation (SD) (n = 4) of bulk density (ρ_b), and total Porosity (Φ) in three different soil depths.

	ρ_b g cm^{-3}			Φ vol.%		
	20 cm	40 cm	80 cm	20 cm	40 cm	80 cm
p-value	**< 0.0001**	**0.0008**	0.9406	**< 0.0001**	**0.0050**	0.3570
Con1	1.46 ± 0.04 a	1.50 ± 0.04 a	1.45 ± 0.04 a	45.0 ± 1.6 c	43.4 ± 1.8 b	44.9 ± 1.8 a
Con2	1.47 ± 0.05 a	1.46 ± 0.05 abc	1.50 ± 0.05 a	45.0 ± 1.8 bc	45.2 ± 2.4 ab	43.9 ± 1.9 a
MinFert	1.46 ± 0.07 ab	1.47 ± 0.06 a	1.48 ± 0.05 a	45.0 ± 2.8 c	44.9 ± 2.4 ab	44.6 ± 1.7 a
Biochar	1.46 ± 0.07 ab	1.43 ± 0.12 abc	1.43 ± 0.03 a	44.9 ± 1.7 c	44.3 ± 4.0 ab	46.6 ± 1.1 a
BioMin	1.41 ± 0.08 abc	1.43 ± 0.12 abc	1.50 ± 0.06 a	46.0 ± 2.6 bc	45.1 ± 4.4 ab	44.0 ± 1.9 a
Clay	1.40 ± 0.08 abcd	1.44 ± 0.05 abc	1.48 ± 0.06 a	46.7 ± 2.8 bc	46.0 ± 1.9 ab	45.4 ± 2.7 a
ClayMin	1.49 ± 0.01 a	1.47 ± 0.04 ab	1.49 ± 0.04 a	43.6 ± 1.0 c	44.4 ± 1.4 ab	48.4 ± 5.9 a
ClayBio	1.40 ± 0.01 abc	1.40 ± 0.02 abc	1.48 ± 0.04 a	46.0 ± 1.7 bc	46.2 ± 0.8 ab	45.2 ± 2.5 a
ClBioMi	1.35 ± 0.07 abcd	1.36 ± 0.06 abc	1.46 ± 0.05 a	48.0 ± 3.4 abc	47.2 ± 2.0 ab	46.1 ± 2.8 a
Manure	1.25 ± 0.04 d	1.30 ± 0.10 abc	1.51 ± 0.04 a	52.5 ± 1.6 a	49.3 ± 3.8 ab	43.6 ± 1.7 a
ManMin	1.40 ± 0.07 abcd	1.24 ± 0.15 c	1.51 ± 0.10 a	46.6 ± 2.1 bc	51.2 ± 4.6 ab	43.1 ± 3.6 a
BioMan	1.31 ± 0.09 bcd	1.31 ± 0.01 abc	1.48 ± 0.06 a	48.7 ± 2.9 abc	49.6 ± 0.5 ab	44.3 ± 1.7 a
BiMaMi	1.27 ± 0.07 cd	1.25 ± 0.16 bc	1.46 ± 0.05 a	50.8 ± 2.8 ab	51.4 ± 5.8 a	44.5 ± 1.7 a

***p*-values printed in bold indicate statistical significance (ANOVA, *p* < 0.05), mean values labeled by the same letter in the same column are not significantly different (Tukey HSD, α = 0.05).**

When comparing θ_{fc} and θ_{pwp} in different soil depths, no significant differences within the planting holes were observed. Goat manure addition, regardless of any further soil conditioner, significantly increased θ_{fc} and θ_{pwp} when compared with the untreated soil at 80 cm soil depth (data not shown).

Despite the significant increase of θ_{fc}, and θ_{pwp}, no treatment effect was detected on the θ_a at 20 cm ($p = 0.131$) as well as at 40 cm ($p = 0.375$).

Water content at permanent wilting point (θ_{pwp}) and θ_{fc} showed a strong positive correlation, $R^2 = 0.75$, among all treatments and soil depths (Figure 4.1).

Table 4.3: ANOVA *p*-values, mean values and SD (n = 4) of water content at field capacity (θ_{fc}), and at permanent wilting point (θ_{pwp}) in three different soil depths.

	θ_{fc} vol.%			θ_{pwp} vol.%		
	20 cm	40 cm	80 cm	20 cm	40 cm	80 cm
p-value	**0.0002**	**0.0161**	0.7920	**< 0.0001**	**< 0.0001**	0.3850
Con1	4.0 ± 1.3 b	3.9 ± 1.2 a	4.1 ± 1.2 a	1.3 ± 0.2 b	1.4 ± 0.4 d	1.5 ± 0.5 a
Con2	3.3 ± 0.7 b	3.5 ± 1.0 a	3.5 ± 1.0 a	1.6 ± 0.2 b	1.3 ± 0.2 d	1.6 ± 0.3 a
MinFert	3.3 ± 1.1 b	3.3 ± 1.1 a	3.4 ± 1.2 a	1.5 ± 0.2 b	1.6 ± 0.3 cd	1.7 ± 0.3 a
Biochar	5.3 ± 1.0 b	5.2 ± 1.0 a	4.8 ± 1.2 a	2.3 ± 0.1 ab	2.3 ± 0.4 bcd	1.8 ± 1.0 a
BioMin	5.7 ± 2.1 b	4.1 ± 1.0 a	4.0 ± 1.2 a	2.7 ± 1.1 ab	1.9 ± 0.6 cd	1.4 ± 0.2 a
Clay	9.0 ± 3.6 ab	8.0 ± 2.4 a	5.2 ± 1.9 a	5.2 ± 1.3 ab	4.7 ± 1.2 abcd	2.5 ± 2.0 a
ClayMin	5.1 ± 2.2 b	4.1 ± 1.5 a	3.5 ± 1.0 a	2.7 ± 1.4 ab	2.7 ± 1.8 abcd	1.8 ± 0.6 a
ClayBio	9.4 ± 3.2 ab	9.7 ± 2.1 a	6.8 ± 6.9 a	5.7 ± 1.9 ab	5.5 ± 1.1 abcd	1.4 ± 0.4 a
ClBioMi	12.9 ± 6.4 a	11.6 ± 5.7 a	4.9 ± 1.0 a	7.0 ± 5.7 a	5.8 ± 2.2 abcd	1.7 ± 0.2 a
Manure	9.2 ± 1.6 ab	8.6 ± 1.4 a	4.9 ± 1.7 a	7.2 ± 1.2 a	6.7 ± 0.7 abc	2.5 ± 0.2 a
ManMin	5.6 ± 1.3 b	13.1 ± 10.3 a	5.0 ± 1.8 a	3.7 ± 1.4 ab	7.7 ± 4.3 a	2.2 ± 0.3 a
BioMan	8.6 ± 3.7 ab	8.4 ± 5.7 a	5.1 ± 0.8 a	5.6 ± 2.2 ab	6.0 ± 2.1 abcd	2.2 ± 0.7 a
BiMaMi	8.9 ± 2.5 ab	13.1 ± 9.6 a	4.2 ± 1.6 a	6.8 ± 1.7 a	7.3 ± 4.4 ab	1.8 ± 0.3 a

***p*-values printed in bold indicate statistical significance (ANOVA, $p < 0.05$), mean values labeled by the same letter in the same column are not significantly different (Tukey HSD, α = 0.05).**

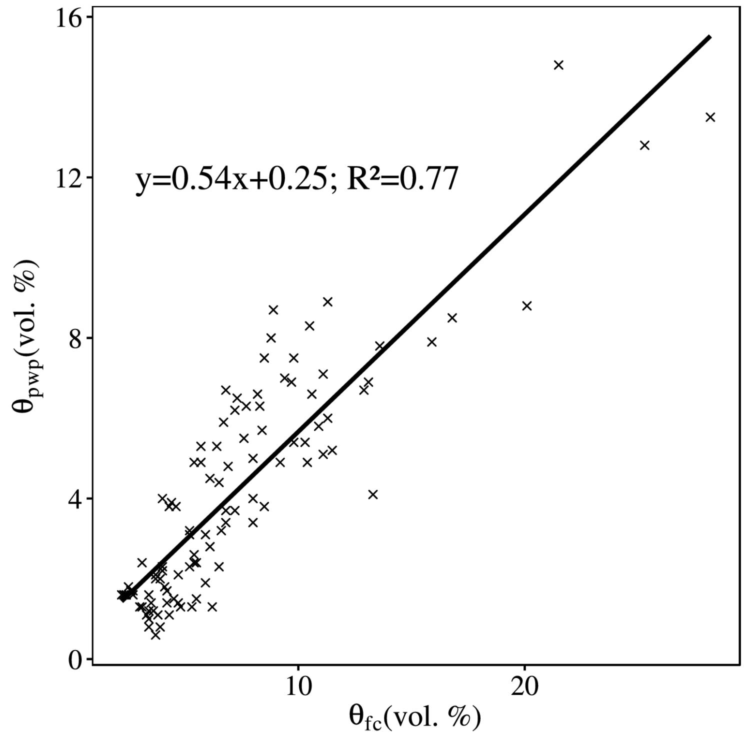

Figure 4.1: Linear regression of water content at field capacity ($\theta_{fc,}$), and water content at permanent wilting point (θ_{pwp}) at 20 cm and 40 cm soil depth.

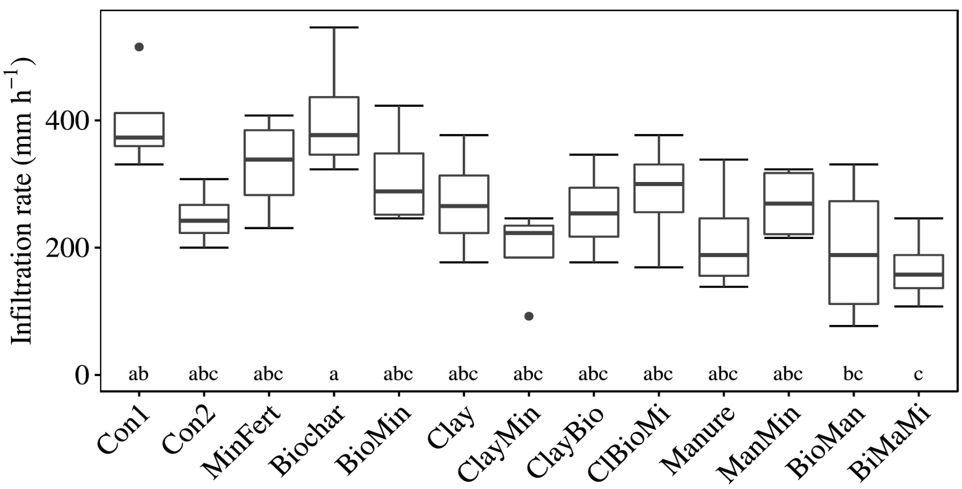

Figure 4.2: Infiltration rates estimated with the Beerkan method (n = 4). Treatments labeled with the same letter are not significantly different (α = 0.05) by Tukey HSD test.

Infiltration

Treatments affected the infiltration rates significantly ($p = 0.006$). BiMaMi significantly reduced the infiltration rate compared to Con1, and Biochar. Compared with the highest infiltration rate of Biochar, BioMan significantly reduced infiltration rate as well (Figure 4.2).

Soil water content

In all consecutive months during the observation period the monthly mean volumetric soil water content differed significantly between treatments (Table 4.4). The addition of goat manure, regardless of any further soil conditioner, significantly increased mean soil water content compared to the control treatments, biochar, and clay substrate treatments. Neither biochar nor the clay substrate addition significantly increased water content compared to the control treatments. Significantly increased mean water content within the planting holes with goat manure was observed regardless of the amount of precipitation (Table 4.4). The mean water content of planting holes treated with goat manure, except in combination with mineral fertilizer, remained above the θ_{fc} in all consecutive months. In planting holes treated with clay substrate in combination with biochar the mean water content almost exclusively remained below the θ_{pwp}.

The time span until the mean soil water content reached the corresponding θ_{pwp} showed a significant treatment effect ($p < 0.001$). The mean soil water content of five treatments remained above θ_{pwp} within 480 h: Con1, Con2, MinFert, BioMin, and ClayMin (Table 4.5). ClayBio, and ClBioMi treatments significantly reduced water retention capacity over time and none of the treatments increased their water retention capacity within the planting hole when compared to the control treatments (Table 4.5).

Table 4.4: Monthly precipitation, ANOVA *p*-values, and mean volumetric soil water content [vol.%] per month within planting holes and SD (n = 4).

	June13	July13	Aug13	Sept13	Oct13	Nov13	Dec13	Jan14	Feb14	Mar14
Precipitation [mm]	0.0	15.6	5.6	0.4	19.4	0.6	94.4	6.0	10.4	5.8
p-value	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
Con1	2.8 ± 0.3 c	5.5 ± 0.3 c	5.0 ± 0.4 c	4.2 ± 2.0 c	4.3 ± 0.5 c	3.0 ± 0.3 b	5.2 ± 0.4 b	4.0 ± 0.2 b	3.2 ± 0.2 b	3.2 ± 0.3 b
Con2	2.5 ± 0.3 c	5.2 ± 0.6 c	4.2 ± 0.2 c	3.0 ± 0.3 c	4.0 ± 0.5 c	2.8 ± 0.2 b	4.9 ± 0.3 b	3.6 ± 0.3 b	3.0 ± 0.2 b	3.0 ± 0.3 b
MinFert	3.7 ± 0.6 c	5.6 ± 0.9 c	5.6 ± 0.5 c	4.1 ± 0.4 c	4.5 ± 0.8 c	3.3 ± 0.5 b	4.7 ± 0.3 b	3.6 ± 0.2 b	2.7 ± 0.3 b	2.8 ± 0.3 b
Biochar	2.8 ± 0.9 c	5.9 ± 1.1 c	4.9 ± 1.8 c	3.0 ± 1.0 c	4.5 ± 1.5 c	2.8 ± 0.8 b	5.4 ± 1.0 b	3.7 ± 0.8 b	3.0 ± 0.7 b	3.0 ± 0.8 b
BioMin	3.4 ± 0.7 c	5.5 ± 0.8 c	6.3 ± 0.9 c	4.4 ± 0.2 c	4.2 ± 0.2 c	2.9 ± 0.6 c	4.9 ± 0.6 b	3.3 ± 0.3 b	2.6 ± 0.6 b	2.7 ± 0.5 b
Clay	3.6 ± 0.3 c	6.2 ± 0.3 c	5.6 ± 0.6 c	4.0 ± 0.4 c	4.8 ± 0.4 c	3.8 ± 0.3 b	6.5 ± 0.5 b	4.7 ± 0.4 b	4.2 ± 0.3 b	4.1 ± 0.4 b
ClayMin	5.4 ± 0.9 c	8.5 ± 1.8 c	7.5 ± 1.5 c	5.3 ± 1.1 c	4.9 ± 0.4 c	4.0 ± 0.8 b	6.2 ± 0.8 b	5.8 ± 1.5 b	4.4 ± 1.2 b	4.1 ± 0.9 b
ClayBio	2.9 ± 0.8 c	7.0 ± 1.2 c	4.8 ± 1.3 c	3.4 ± 0.8 c	4.2 ± 1.0 c	3.1 ± 0.7 b	5.5 ± 0.9 b	4.1 ± 0.7 b	3.4 ± 0.6 b	3.4 ± 0.6 b
ClBioMi	4.5 ± 0.3 c	7.0 ± 0.8 c	6.0 ± 0.5 c	4.4 ± 0.6 c	4.9 ± 0.5 c	3.9 ± 0.5 b	6.4 ± 0.6 b	5.1 ± 0.9 b	4.3 ± 0.6 b	4.2 ± 0.5 b
Manure	15.8 ± 3.4 ab	20.2 ± 3.3 ab	26.7 ± 3.3 ab	24.1 ± 3.5 ab	26.0 ± 4.3 a	21.2 ± 4.6 a	20.4 ± 4.3 a	17.1 ± 4.5 a	15.7 ± 4.2 a	14.3 ± 3.9 a
ManMin	17.6 ± 4.0 ab	22.1 ± 4.0 a	22.5 ± 5.7 ab	23.6 ± 3.6 ab	24.1 ± 0.9 ab	20.5 ± 1.5 a	18.8 ± 2.9 a	14.5 ± 3.5 a	12.9 ± 2.8 a	12.5 ± 2.2 a
BioMan	12.0 ± 2.8 b	15.4 ± 4.5 b	20.0 ± 4.7 b	18.2 ± 4.8 b	19.9 ± 5.3 b	17.2 ± 5.2 a	17.2 ± 3.8 a	15.0 ± 5.3 a	13.3 ± 5.2 a	12.1 ± 5.0 a
BiMaMi	19.5 ± 5.5 a	20.7 ± 4.8 ab	27.5 ± 4.8 a	25.2 ± 6.0 a	26.9 ± 4.5 a	22.4 ± 3.8 a	21.5 ± 2.8 a	17.2 ± 3.0 a	15.4 ± 2.1 a	13.9 ± 2.4 a

***p*-values printed in bold indicate statistical significance (ANOVA, *p* < 0.05), mean values labeled by the same letter in the same column are not significantly different (Tukey HSD, α = 0.05).**

Continue Table 4.4.

	Apr14	May14	June14	July14	Aug14	Sept14	Oct14	Nov14	Dec14	Jan15
Precipitation [mm]	83.2	23.4	5.8	47.2	27.6	20.4	2.2	40.2	15.2	8.0
p-value	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
Con1	5.7 ± 0.6 b	4.9 ± 0.6 b	3.2 ± 0.3 b	4.3 ± 0.3 b	6.7 ± 0.3 b	4.8 ± 0.3 b	3.3 ± 0.3 b	5.4 ± 0.2 b	4.1 ± 0.2 b	3.3 ± 0.4 c
Con2	5.6 ± 1.0 b	4.5 ± 0.6 b	3.1 ± 0.2 b	4.0 ± 0.3 b	6.2 ± 0.7 b	4.8 ± 0.7 b	3.3 ± 0.3 b	4.9 ± 0.4 b	4.4 ± 0.9 b	3.3 ± 0.3 c
MinFert	5.1 ± 0.7 b	4.2 ± 0.7 b	2.7 ± 0.3 b	3.8 ± 0.3 b	5.9 ± 0.3 b	5.1 ± 0.5 b	3.4 ± 0.4 b	4.7 ± 0.3 b	4.0 ± 0.3 b	2.9 ± 0.1 c
Biochar	6.1 ± 1.1 b	4.6 ± 1.1 b	3.0 ± 0.8 b	4.3 ± 0.8 b	6.9 ± 1.1 b	4.5 ± 4.5 b	3.1 ± 0.7 b	5.2 ± 0.8 b	4.0 ± 0.7 b	3.3 ± 0.6 c
BioMin	5.8 ± 0.9 b	4.3 ± 0.5 b	2.7 ± 0.6 b	3.9 ± 0.4 b	6.2 ± 0.5 b	4.4 ± 1.0 b	2.8 ± 0.5 b	2.7 ± 0.6 b	4.2 ± 0.7 b	3.1 ± 0.5 c
Clay	6.4 ± 1.0 b	5.3 ± 0.4 b	4.1 ± 0.2 b	5.1 ± 0.4 b	7.3 ± 1.3 b	5.2 ± 0.5 b	4.2 ± 0.5 b	6.1 ± 0.6 b	4.9 ± 0.4 b	4.1 ± 0.2 bc
ClayMin	5.8 ± 0.5 b	5.3 ± 0.8 b	4.2 ± 0.9 b	5.3 ± 0.9 b	7.5 ± 1.1 b	6.1 ± 1.5 b	4.7 ± 1.4 b	5.8 ± 0.4 b	5.0 ± 0.9 b	4.1 ± 0.9 bc
ClayBio	5.2 ± 0.8 b	4.4 ± 0.7 b	3.4 ± 0.4 b	4.4 ± 0.4 b	6.4 ± 0.7 b	4.7 ± 0.4 b	3.7 ± 0.5 b	5.4 ± 0.3 b	4.5 ± 0.4 b	3.6 ± 0.4 bc
ClBioMi	6.2 ± 0.2 b	5.3 ± 0.2 b	4.2 ± 0.4 b	5.5 ± 0.1 b	7.4 ± 1.0 b	6.0 ± 1.1 b	4.7 ± 0.3 b	6.1 ± 0.4 b	5.2 ± 0.7 b	4.2 ± 0.4 bc
Manure	17.5 ± 3.9 a	17.6 ± 4.3 a	15.1 ± 4.3 a	15.4 ± 4.5 a	16.3 ± 4.1 a	14.4 ± 3.7 a	12.5 ± 2.7 a	13.1 ± 3.3 a	11.6 ± 2.4 a	9.3 ± 3.0 a
ManMin	15.2 ± 1.4 a	15.7 ± 2.2 a	13.6 ± 2.5 a	13.8 ± 2.1 a	14.2 ± 2.4 a	12.4 ± 2.2 a	10.4 ± 2.4 a	10.1 ± 2.0 a	9.7 ± 3.5 a	7.6 ± 3.0 ab
BioMan	16.1 ± 6.6 a	16.2 ± 5.8 a	14.1 ± 5.1 a	14.3 ± 5.3 a	14.9 ± 4.1 a	13.0 ± 3.7 a	11.3 ± 3.6 a	12.1 ± 3.6 a	11.3 ± 3.3 a	8.8 ± 3.8 a
BiMaMi	16.8 ± 2.3 a	17.7 ± 1.4 a	15.9 ± 1.4 a	15.4 ± 1.5 a	17.8 ± 0.6 a	16.3 ± 0.4 a	13.2 ± 0.7 a	13.9 ± 1.5 a	13.2 ± 1.0 a	11.1 ± 1.3 a

***p*-values printed in bold indicate statistical significance (ANOVA, *p* < 0.05), mean values labeled by the same letter in the same column are not significantly different (Tukey HSD, α = 0.05).**

Table 4.5: Time span (h, means ± SD, n = 4) needed for the soil water to reach θ_{pwp}. Mean values labeled by the same letter are not significantly different (Tukey HSD, α = 0.05).

	Period (h) until reaching θ_{pwp}	
Con1	◊	a
Con2	◊	a
MinFert	◊	a
Biochar	446.3 ± 57.9	a
BioMin	◊	a
Clay	198.0 ± 113.2	ab
ClayMin	◊	a
ClayBio	19.5 ± 21.6	b
ClBioMi	31.5 ± 34.4	b
Manure	282.0 ± 238.7	ab
ManMin	241.5 ± 275.4	ab
BioMan	162.0 ± 226.3	ab
BiMaMi	384.5 ± 192.0	a

In treatments labeled with ◊ none of the replicates reached θ_{pwp} within 480 h.

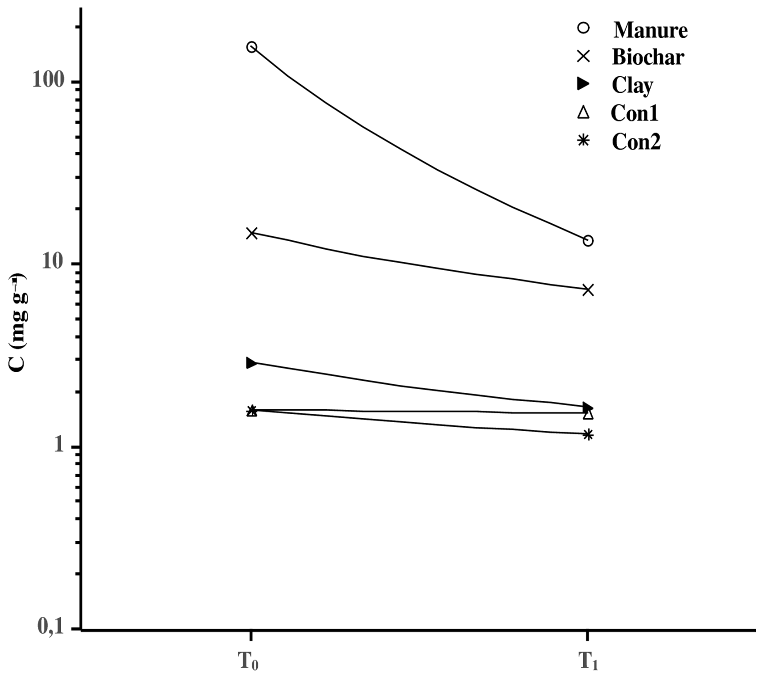

Figure 4.3: Course of soil C depletion within 16 months. Ordinate is logarithmic scaled.

Soil carbon

In all five treatments that were examined, a loss of C stock occurred during the complete cycle of dry and rainy season (Figure 4.3). The greatest loss of C stock was observed within the Manure treatment. After 16 months, 13.5mg C g^{-1} of the initial 156.6 mg C g^{-1} was detected, which was a loss of 93 % of C stock, whereas in the Con1 treatment the C stock got reduced from 1.6 mg C g^{-1} to 1.5 mg C g^{-1}, a loss of 4.5 %. In the Biochar treatment, a loss of 51.4 % of C stock was measured. In the Clay and Con2 treatment, a loss of 43.0 % and 26.8 % was detected.

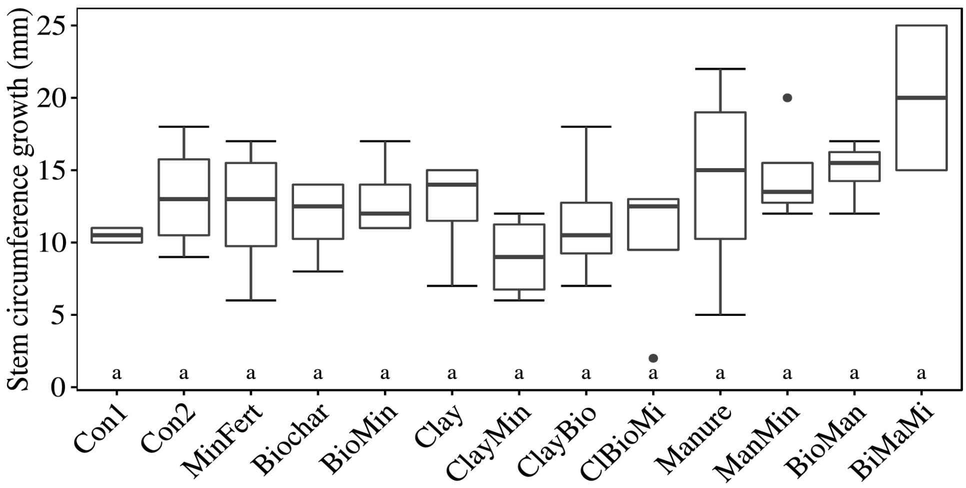

Figure 4.4: Shoot circumference growth within 23 months (n = 4). Treatments labeled with the same letter are not significantly different (α = 0.05) by Tukey HSD test.

Seedling growth

The growth of the stem circumference of *S. tuberosa* seedlings was 12.9 mm on average over 23 months. Treatments had no significant effect on stem growth ($p = 0.31$). However, the goat manure addition led to the highest growth in stem circumference by trend (Figure 4.4).

Seedling survival

Of the 130 planted seedlings, 75 % survived 23 months until the last inventory in March 2015. The survival probability 23 months after planting was 1 for ClayMin, and ManMin, 0.9 for Con1, 0.8 for BiMaMi, Clay, Con2, and MinFert, 0.7 for BioMin, and ClBioMi, 0.6 for

Biochar, BioMan, and Manure, and 0.5 for ClayBio. Comparing the survival functions, no significant differences between treatments were detected ($p = 0.29$).

4.4 Discussion

Soil physical parameters

This experiment illustrates that porous goat manure mixed at 40 % v/v with the Arenosol reduces ρ_b because it increases Φ in the planting hole. The results show consistency in the relation of reduced ρ_b due to increased Φ for Manure and BiMaMi at 20 cm as well as at 40 cm soil depth. As θ_{pwp} increased significantly and AC as well as θ_{fc} showed no significant change among the goat manure treatments, the observed increase in Φ resulted from an increased number of micro pores. This is concurrent with results for other organic matter used as a soil conditioner (*Asghari et al.*, 2009).

Abel *et al.* (2013) reported reduced ρ_b, increased Φ, and improved water-holding capacity after biochar application at rates of 1 – 5 % w/w on sandy soils. In contrast, no effect of biochar application on water-holding capacity nor evidence of changes in ρ_b and Φ were found in two field experiments (*Hardie et al.*, 2014; *Jones et al.*, 2012). In our experiment, the biochar application rate of 5 % v/v, which equals 1.25 % w/w, did not significantly affect these soil parameters as well. The transport of biochar particles into deeper soil layers by percolate water in coarse-textured soils (*Leifeld et al.*, 2007) can be ruled out because no significant treatment effect on the soil physical parameters in 80 cm soil depth was reported. We argue that the biochar produced under low-tech conditions was pyrolyzed at a rather low temperature (less than 600°C), which affects its properties. It is known that temperature during pyrolysis influences the presence of internal pyrogenic nanoporosity of biochar as well as aliphatic compounds on the surface of the biochar matrix (*Gray et al.*, 2014). A high temperature leads to more pyrogenic nanopores and reduces the presence of aliphatic compounds, which are correlated with hydrophobicity in biochar (*Kinney et al.*, 2012). The lack of biochar effect on ρ_b and Φ in our experiment might be explained by the low content of pyrogenic nanopores and the potential hydrophobicity of the biochar used, caused no effect on θ_{fc}. The latter was confirmed by the WDPT test conducted after the experiment. Consequently, the biochar used in the experiment was hydrophobic and little porous, therefore lacking potential for amelioration.

According to McKissock *et al.* (2002), low initial clay content of the experimental soil as well as the dominance of smectite in the clay fraction favor the effectiveness of clay addition on reduction of water repellency of sandy soils. Even though the experimental Arenosol contained less than 5 % clay and smectite was the principal mineral in the clay fraction, the addition of 10 % v/v clay substrate resulted in no significant effect on the tested soil physical properties. In contrast Abdel-Nasser *et al.* (2007) and Mojid *et al.* (2012) reported enhanced θ_{fc} as a function of increasing clay content in sandy soils. The authors reported maximum θ_{fc} after adding 10 % w/w clay in a laboratory experiment and 15 % v/v in a field experiment as well as increasing Φ and decreasing ρ_b with increasing clay content. The experimental soils of both studies had a higher initial content of fine particles (< 0.02 mm), 17.6 % and 20.5 % respectively, whereas the fine particles content of the Arenosol used in this study was 4.7 %. Accordingly, the clay substrate treatments, containing approximately 14.7 % fine particles, included fewer fine particles than the untreated soils of the two consulted studies. The lack of clay effect could be due to the very low application rate of clay substrate.

Increasing infiltration and K_{fs} of an eroded soil due to manure application was reported in Arriaga & Lowery (2003). Conversely, the manure application in our study tended to reduce infiltration into the planting hole in coarse sandy soils, < 200 mm h^{-1}. This was likely due to a higher number of micro pores, which led to an increased θ_{pwp}. The increased micro-porosity, under the given conditions, led to a less coarse-textured soil fabric which reduced the infiltration and K_{fs}. As a result, manure addition, with or without biochar, decelerated the percolation of irrigation and rain water in the planting hole and increased the retention period of water in the planting hole.

The volumetric soil water content was significantly affected by goat manure addition. However, the change in θ_{fc} determined at the end of the experiment cannot explain the observed increased soil water content in the planting hole since the measured soil water content of treatments with goat manure were above the θ_{fc}. The soil carbon content strongly influences the water-holding capacity and water availability (*Rawls et al.*, 2003), and we argue the initial θ_{fc} of planting holes treated with goat manure were different. Since a soil C loss in the first 16 months of 91.4 % was observed within the Manure treatment, the θ_{fc} may have changed by the same magnitude over time. Thus, the course of volumetric soil water content in planting holes treated with goat manure most likely mirrors the change in θ_{fc} over time in these treatments.

Clay substrate in combination with biochar led to water content in the planting hole below the PWP and negatively affected water retention over time (Table 4.5). This observation may have resulted from higher evaporation due to the biochar application, since Basso *et al.* (2013) observed increased evaporation with a biochar application in sandy loam, with a tendency for increased PWP.

Due to the correlation of θ_{fc} and θ_{pwp}, the θ_a remained unchanged. The increased θ_{fc} is achieved through increased micro-porosity, which makes modifying the agriculturally important target parameter θ_a *in-situ* with biochar, clay or manure difficult.

Plant parameters

The slow growth in stem circumference of *S. tuberosa* without significant differences between different soil water content and initial nutrient supply underlines its "low nutrient" and "low water" strategies and indicates its adaptation to infertile soils and economical water use via strict stomatal control (*Lima Filho*, 2004; *Reich*, 2014). This emphasizes the nondomesticated character of the plant material and could explain the lack of treatment effects on stem growth of *S. tuberosa* under field conditions. Drumond *et al.* (2001) reported no response in *S. tuberosa* stem growth due to additional irrigation and P and N fertilization in their 40-month field experiment. In pot experiments, however, *S. tuberosa* shows growth responds to mineral fertilization (*Neves et al.*, 2008b, 2007b, 2007a).

Seedling survival has been reported to be very low in semiarid regions, but improvable with low-tech planting techniques or site preparation, such as microcatchments or mulching (*Bakker et al.*, 2012; *Valdecantos et al.*, 2014). In contrast, the seedling survival of *S. tuberosa* in this experiment was not improved by any treatment. However, the observed net seedling survival of 75 % after 23 months cannot be viewed low. Since the combination of weekly irrigation, and precipitation maintained water content in almost all treatments above PWP, the observed dieback cannot be explained by drought stress, and reasons remain uncertain.

The nondomesticated character of the available plant material makes *S. tuberosa* an ideal species for low-input or low-tech orchards within the Caatinga. Especially if water supply is discontinuous and advanced irrigation technologies are unavailable or unaffordable for smallholders. The robust plant material appears to also be well suited for reforestation purposes.

4.5 Conclusion

Increased volumetric water content in planting holes due to manure addition could be a benefit for tree planting in coarse-textured sands under hot semiarid climates in general. According to our results, the use of clay substrate in combination with biochar to improve soil physical parameters of sand under these conditions did not improve the soil but cause obstructive effects. Application of biochar or clay at the given rates is not recommended because of the laborious sourcing and lack of soil physical benefits. However, the seedlings of the largely undomesticated *S. tuberosa* did not respond to increased volumetric soil water content or initial nutrient availability. Stem growth and survival remained unaffected. Due to its robust traits and strong survival without anthropogenic support, the available plant material of *S. tuberosa* is suitable for reforestation purposes under water limited conditions and also holds benefits for its use in extensive orchards as income alternatives for Caatinga dwellers.

Acknowledgements

This work was supported by the German-Brazilian joint research project INNOVATE (Interplay among multiple uses of water reservoirs via innovative coupling of aquatic and terrestrial ecosystems). The project is funded by the German Federal Ministry of Education and Research (BMBF) under project number 01LL0904B. The first author would also like to thank for support by the Foundation fiat panis Ulm, Germany. Additionally, the authors would like to thank Dr. Francisco Pinheiro de Araújo and Embrapa semiárido (Embrapa-CPATSA) for the supply of the plant material used in present study. As well as Dr. Geraldo Majella Bezerra Lopes and the Instituto Agronômico de Pernambuco – IPA for the provision of workspace and support for the soil physical analysis.

5. Comparison of Soil Amendments for Reforestation with a Native Multipurpose Tree Under Semiarid Climate: Root and Root Tuber Response of *Spondias tuberosa*

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Abstract

The Caatinga biome, characterized by a species-rich seasonally dry tropical forest, but highly disturbed covers most of Brazil's Northeast. Endemic to this biome is the multipurpose tree *Spondias tuberosa* Arr., which forms numerous root tubers to resist drought stress. In order to develop improved soil management for reforestation with *S. tuberosa* the response of its root system to different soil amendments was studied with 52 seedlings, using goat manure, clay substrate, biochar as soil amendments, and mineral fertilizer. The default root architecture of three-year-old *S. tuberosa* and the relation between soil physical parameters and fine root dry matter (≤ 2 mm), root length density, root tuber volume, root tuber fresh weight, and shoot-root ratio were analyzed.

Seedlings still formed a tap root with a maximum rooting depth of 63 cm and a maximum horizontal extent of 35 cm, developing 2 to 4 root tubers per seedling. Fine root dry matter in 3000 cm^3 soil samples differed significantly, ranging from 0.23 g in the control to 0.03 g in the treatment combining manure with biochar and mineral fertilizer. According to the orthogonal contrast, manure was the pivotal soil amendment affecting fine root dry matter negatively. Simultaneously, manure application led to increased soil water content compared to treatments without. The shoot-root ratio increased by 32 % compared to the control, when *S. tuberosa* was grown in wet soils. Root tuber growth was significantly enhanced by manure addition. This effect is attributed to a reduction of soil bulk density as root tuber volume exhibited a negative correlation with soil bulk density. There was no statistical relationship between root tuber volume and seedling survival during the field experiment. Compared with the control, neither clay, biochar nor solely mineral fertilization significantly affected root growth.

Soil management focused on improving water availability is suspected of hampering fine root growth of *S. tuberosa* seedlings, whereas reducing soil bulk density enables better root tuber development and could, therefore, be a promising measure to increase *S. tuberosa* drought resistance in the long term for more successful reforestation. Disregarding its negative impact on fine root growth, we assume manure is the most promising amendment among the tested treatments, due to its positive effect on root tuber growth.

Keywords: Umbuzeiro, drylands, amelioration, root plasticity, hydrotropism

Published in *Forest Ecology and Management*, 396, 1–10, 2017. The electronic version of this article is the definitive one, available at: http://dx.doi.org/10.1016/j.foreco.2017.04.010. With kind permission of Elsevier B.V.

5.1 Introduction

The growing human populations in semiarid regions increases the demand for food, putting pressure on such regions by requiring more cropland and livestock products and promoting habitat degradation (*Hudson*, 1987). Climate change-induced droughts within semiarid regions are suspected of enhancing this ongoing degradation (*Fraser et al.*, 2011; *IPCC*, 2007b). The northeast Brazilian semiarid Caatinga biome, covering 845,000 km^2, facing already severe habitat degradation, which resulted in up to 80 % loss of its native seasonally dry tropical forest and desertification in 20 % of its area (*Franca-Rocha et al.*, 2007; *IBGE*, 2004; *Sá et al.*, 2010). Further, loss of native vegetation has led to reduced soil fertility due to a reduction of soil carbon stocks in the Caatinga (*Giongo et al.*, 2011; *Sampaio*, 1995; *Tiessen et al.*, 1998), with a probable severe impact on the national food supply, since 70 % of food crops for the domestic market are produced by smallholders in the region (*Sietz et al.*, 2011).

Endemic to this biome is the xeromorphic multipurpose tree *Spondias tuberosa*, which, due to its fruit formation and as a source for seed oil has great agro-industrial potential (*Borges et al.*, 2007; *Cavalcanti*, 2008; *Lima*, 1996; *Prado and Gibbs*, 1993). To date, however, the knowledge about its cultivation is rudimentary and its monetary contribution to rural livelihood has virtually been limited to extractivism (*Mertens et al.*, 2015). Yet, due to its drought resistance and multipurpose character, the tree is a promising species for use in agroforestry and for reforestation within the Caatinga. We assume that utilization of *S. tuberosa* can help to slow further habitat degradation and, simultaneously, provide an income source for Caatinga dwellers.

Common strategies of trees to avoid drought stress focus on balanced water loss and water uptake. The former is achieved by strict regulation of stomatal closure or restricted shoot growth. In order to increase water uptake, trees enhance fine root growth, develop deep taproots or lower water potential in their root tissue (*Brunner et al.*, 2015). *S. tuberosa* exhibits strict and accentuated stomata regulation and forms root tubers, which store assimilates, water and minerals, as a drought avoidance strategy in its semiarid habitat (*Epstein*, 1998; *Lima Filho*, 2004, 2001, *Silva et al.*, 2009b, 2009a). The root architecture of *S. tuberosa* is rather unorthodox for drought adapted trees, since saplings do not form a deep rooting system but, rather, spread shallow (< 2 m) roots in a horizontal direction (*Brunner et al.*, 2015; *Cavalcanti et* *al.*, 2010; *Schenk and Jackson*, 2002). The formation and development of root tubers by *S. tuberosa* is known to be more pronounced in the early years of development than in later stages (*Cavalcanti et al.*, 2010), but soil physical and soil chemical stimuli that affect the formation and development of its root tubers remain unknown. Moreover, there is no knowledge about whether the presence of root tubers affects the vigor of *S. tuberosa* seedlings. Information is also lacking about the response of *S. tuberosa* fine roots (≤ 2 mm) and shoot-root ratio to nutrient availability, which has already been considerably researched regarding trees from wet tropical forests (*Kochsiek et al.*, 2013; *Santiago et al.*, 2012; *Sayer et al.*, 2012; *Wurzburger and Wright*, 2015; *Yavitt et al.*, 2011).

In order to develop cropping systems for agro-industrial purposes including *S. tuberosa* such knowledge is essential. Thus, research is needed regarding the potential effects of soil management and fertilization on the development of the root system of *S. tuberosa*. Application of manure, clay substrate, and biochar has been proven to be able to improve the physical and chemical attributes of sandy soils (*Dempster et al.*, 2012; *Djajadi et al.*, 2012; *Haynes and Naidu*, 1998; *Obia et al.*, 2016; *Tangkoonboribun et al.*, 2006; *Uzoma et al.*, 2011). The ability of manure to improve the hydrological properties of sandy soils is attributed to the porosity of its organic matter and its capacity to absorb water (*Bauer*, 1974; *Khaleel et al.*, 1981). Improved soil hydrological parameters due to clay substrate application have been attributed to the reduced hydrophobicity of sand grains coated with clay minerals and their ability to swell (*McKissock et al.*, 2002; *Young and Smith*, 2000). Therefore we have tested both of these readily available soil amendments regarding their ability to improve soil hydrology properties, which would presumably support establishment and growth of *S. tuberosa* seedlings in a sandy soil on a disturbed Caatinga site. Due to its large surface, biochar affects the nutrient retention of coarse sandy soils (*Uzoma et al.*, 2011; *Yao et al.*, 2012). In addition to water availability, nutrient availability and retention is a growth-limiting factor in the Caatinga; therefore it was investigated whether there is a secondary effect of improved nutrient supply when backfill containing manure or clay substrate is enriched with biochar and/or mineral fertilizer.

This work (1) describes the coarse root system including tubers, and the vertical distribution of root length density (RLD) and fine root dry matter (DM) of three-year-old *S. tuberosa* seedlings. It seeks to examine whether amelioration with manure or clay substrate, in combination with mineral fertilizer and/or biochar, affects (2) the mean size and fresh weight of root tubers per seedling, (3) fine root parameters, and (4) the root-shoot ratio of *S. tuberosa* seedlings. Last it analyzes whether (5) fine root parameters are related to root tuber volume and weight and whether (6) the volume and weight of root tubers correlates with seedling vigor.

5.2 Material and methods

Site description

To study the effects of amelioration on soil physical parameters, the growth, and vigor of *S. tuberosa* seedlings as well as their root architecture, a field experiment was conducted – from 2013 until mid-2016. As location served an anthropogenically disturbed Caatinga site in the municipality of Petrolândia (S8°57'24.1'', W38°15'00.4'', 330 m a.s.l.), situated in the state of Pernambuco. The prevailing climate is hot semiarid, classified as BSh according to Köppen-Geiger (*Grieser*, 2005), with a long-term annual mean temperature and annual precipitation in the city of Petrolândia of 24.3°C and 438 mm, respectively, modeled and interpolated with data from 1982 to 2012 (*Climate-Data.org*, 2016). The mean annual precipitation recorded by Agência Pernambucana de Águas e Clima (APAC) during the same 30-year period Petrolândia (S8°58'27.4'', W38°12'59.3'') was 330 ± 175 mm (mean ± standard deviation) (*APAC*, 2015). During the two-year experiment, an annual mean temperature of 26.6°C, with a monthly variation of less than 5°C, and a mean annual precipitation of 254 mm, distributed erratically throughout the year, was recorded on-site (S8°57'24.63'', W38°15'1.56'') (Figure 5.1). The soil on the experimental field classified as Arenosol, is coarse-textured, with 95.3 % sand, 0.4 % silt, and 4.3 % clay. Its chemical characteristics are poor, with 1.6 mg g^{-1} C, 0.2 mg g^{-1} TN, 0.05 mg g^{-1} P^{CAL}, 0.19 mg g^{-1} K^{CAL}, a low pH value of 5.1 (in H_2O), and low CEC of 0.9 $mmol_c$ kg^{-1} (*Mertens et al.*, 2017).

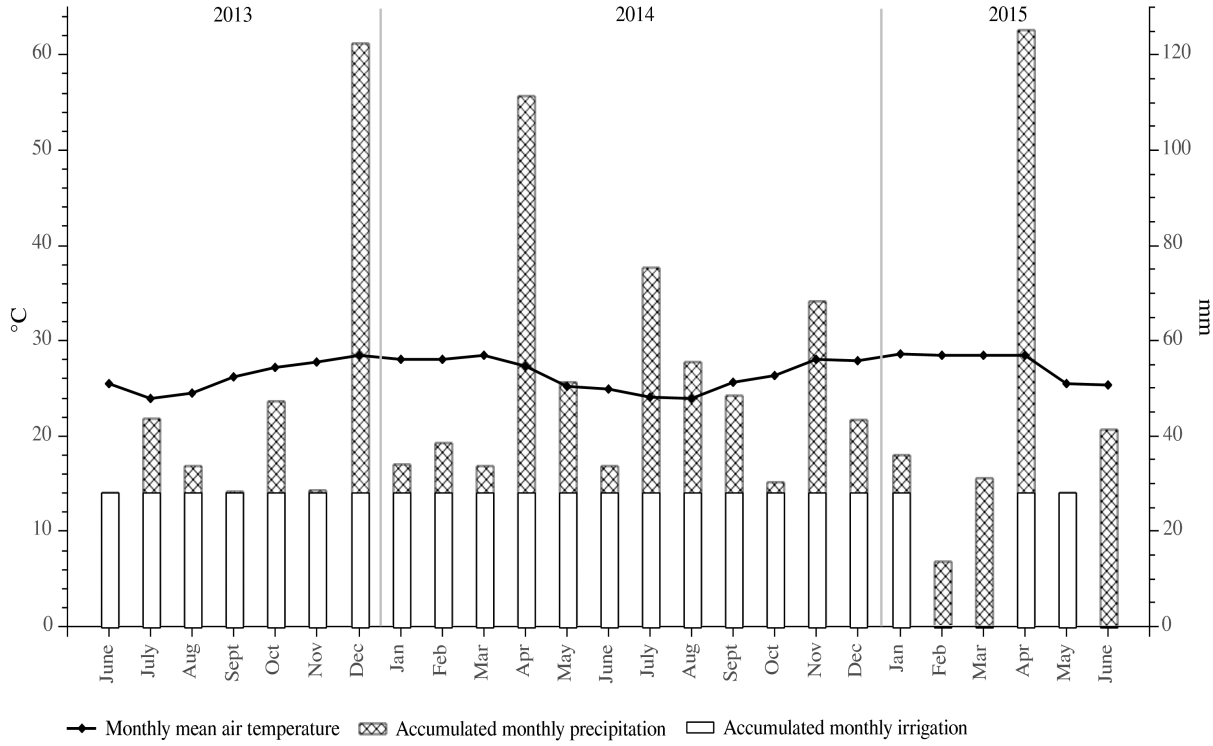

Figure 5.1: Mean monthly air temperature, and distribution of precipitation recorded on-site during the experiment from June 2013 until June 2015, as well as accumulated monthly irrigation.

Experimental design

The root study was conducted on three-year-old *S. tuberosa* seedlings, that were planted in cylindric planting holes (h = 55 cm; r = 30 cm) at the beginning of April 2013. To avoid grazing and browsing damage, the 4 ha experimental field was fenced in January 2013. The planting holes and seedlings were nondestructively monitored from June 2013 onwards. The experiment contained eleven treatments with ten replicates each, including sole addition of manure, clay substrate, biochar, or mineral fertilizer and mixed combinations of these soil amendments, as well as two controls (Table 5.1). In Control 1 (Con1) the seedlings were planted in holes which did not exceed their root ball, whereas Control 2 (Con2) used the spacious planting holes specified above without neither soil amendments nor mineral fertilizer in the backfill. The locations for the planting holes, consecutively numbered, were selected within the patchy Caatinga where natural vegetation was lacking with a minimum distance of 1.5 m to the surrounding vegetation. Thus, additional clearing of the already disturbed Caatinga site was avoided. An effort was made to align the locations in rows with a southwestern orientation within the field, with spacing within each row of 8 m and a distance between rows of 12 m, as long as the already existing vegetation permitted it. One replicate was randomly assigned for each numbered location. For randomized assignment of replicates to locations as well as replicate selection, the random function in Calc from LibreOffice (*The Document Foundation*, 2011) was used, which returns an integer number within a defined range. The seedlings were manually irrigated with 2 l of water once a week until the end of May 2016, with a pause between February and March 2016.

Table 5.1: Control and treatments with their corresponding abbreviations, the volumetric proportion of backfill materials and initial soil chemical parameters of the backfill mix. The refilled planting holes had a volume of 156 l.

Control/ Treatment	Abbreviation	Topsoil %	Goat manure %	Clay substrate %	Biochar %	TN mg g^{-1}	P^{CAL} mg g^{-1}	K^{CAL} mg g^{-1}	C mg g^{-1}*
Control 1 undisturbed soil	Con1	100	–	–	–	0.2	0.05	0.2	1.6
Control 2 disturbed soil	Con2	100	–	–	–	0.2	0.05	0.2	1.6
Mineral fertilizer	MinFert	100	–	–	–	0.4	0.24	0.4	1.6
Biochar	Biochar	95	–	–	5	0.2	0.05	0.2	15.0
Biochar + Mineral fertilizer	BioMin	95	–	–	5	0.4	0.24	0.4	15.0
Clay substrate	Clay	90	–	10	–	0.2	0.05	0.2	2.9
Clay substrate+ Mineral fertilizer	ClayMin	90	–	10	–	0.4	0.24	0.4	2.9
Clay substrate+ Biochar	ClayBio	85	–	10	5	0.2	0.05	0.2	16.6
Clay substrate+ Biochar + Mineral fertilizer	ClBioMi	85	–	10	5	0.4	0.24	0.4	16.6
Goat manure	Manure	60	40	–	–	0.5	0.04	0.2	156.6
Goat manure + Mineral fertilizer	ManMin	60	40	–	–	0.5	0.24	0.4	156.6
Biochar + Goat manure	BioMan	55	40	–	5	0.5	0.04	0.1	183.2
Biochar + Goat manure + Mineral fertilizer	BiMaMi	55	40	–	5	0.5	0.24	0.4	183.2

*** before Urea application. Detailed chemical and physical characteristics of the utilized soil amendments are given in Mertens *et al.* (2017).**

Quantification of fine roots

Root length density (RLD) and fine root DM (≤ 2 mm) of *S. tuberosa* within the planting holes were measured using volumetric soil samples. Samples of 1500 cm^3 substrate were taken at 0 – 30 cm as well as 30 – 60 cm soil depth from all treatments with a bipartite root auger (Eijkelkamp Soil&Water, Giesbeek, the Netherlands). Four replicates from each treatment and soil depth were taken 15 cm offset eastwards of the rootstock in the planting hole. To avoid contamination of each sample with the living fine roots of surrounding vegetation, ample root pruning around the planting hole by digging a 10 cm wide and 1.5 m deep trench was conducted in April 2015, two months before sampling. Due to this extensive root pruning, combined with weeding inside the pruning perimeter, all living fine roots within the sample were considered of *S. tuberosa* origin.

Each entire sample was transferred into a 5 l bucket in which the sand fraction was sedimented. The supernatant, containing the fine roots and the silt and clay fractions, was rinsed through a sieve with 0.5 mm mesh size (Retsch Test Sieve ISO 3310/1; Retsch, Haan, Germany) to filter out fine roots and other substances, among which dead roots, other organic material, and remaining soil residues were removed using forceps and Pasteur pipettes. If visual separation into living and dead fine roots with a precision magnifier (10x) was inconclusive, a judgment was based on root elasticity as well as the degree of cohesion between cortex and periderm (sensu *Persson*, 1978; *Soethe et al.*, 2006). Before the fresh weight of the washed fine root samples was determined, they were dried with paper towels to remove excess water. Afterwards, the samples were kept cool at 5 to 8°C in 15 % Ethanol, until the root scan was completed.

The root scan was carried out with a flatbed scanner set to 600 dpi (HP Scanjet 2400) and transformed into gray-scale images using the image-manipulation software GIMP (*GIMP Developers*, 1995). Root length was measured using the macro IJ_Rhizo (http://www.plant-image-analysis.org/software/IJ_Rhizo), for the Java program ImageJ (http://rsbweb.nih.gov/ij/). In order to use the macro correctly, additional installation of the morphological operators for ImageJ from http://www.mecourse.com/landinig/software/software.html was necessary (*Landini*, 2008; *Pierret et al.*, 2013). The processing parameters of IJ_Rhizo were set according to Pierret *et al.* (2013), except for increasing width of the excluded border to 150 pixels. This was necessary to cut halos from the edges of the DIN A4 acrylic glass tray in which the root samples were placed, which interfered with image analysis during preliminary tests. Further, the default memory assigned to the Java™ engine was increased to 1.7 GB so processing the voluminous images was possible without program stalls. RLD was calculated by dividing the root length per sample by volumetric sample size. Afterwards, fine root samples were oven dried at 65°C for three days, and dry matter was recorded.

Description of coarse root plus root tuber architecture

In order to describe the coarse root system (> 2 mm) of the *S. tuberosa* seedlings grown in undisturbed soil, 100 cm long, 100 cm wide and 120 cm deep pits were dug 20 cm offset from the four replicates of Con1. Prior to the wet excavation of the root system, a pin-frame was inserted into the westward-facing profile to spatially fix the coarse roots. The pin-frame was a further development of the pin-board described by Böhm (1979), and consisted of a T-shaped frame with a 10 × 10 cm grid for the top 40 cm and a 20 × 20 cm grid for the lower 80 cm, covering 0.64 m^2 of the profile. Preliminary investigations have shown that the coarse root system of two- and three-year-old *S. tuberosa* plants do not exceed 60 cm horizontally and 90 cm vertically and the coarse roots rarely exhibits any branching below 40 cm. Thus the chosen size and shape of the pin-frame was considered adequate to cover the entire coarse root system. At each intersection of the grid, 50 cm long pins were welded, which were then inserted into the soil. The spatially fixed coarse roots were wet excavated on-site, since the removal of soil monoliths out of the trench was impossible, due to the poor cohesion of the experimental soil.

The exposed coarse root system was photographed, and the pictures were transformed into silhouettes of the root system using GIMP. Simultaneously, the number of secondary roots, the maximal vertical and horizontal extent of coarse roots, accumulated length of coarse roots, and number of root tubers were recorded on the profile for each sample.

Afterwards, the root tubers from the four replicates of all treatments were harvested, and their fresh weight as well as volume was measured. Any globular departure from the tubular roots was considered a root tuber. Tuber size was measured volumetrically by water displacement in a 3 l graduated beaker. Approximately 13 days elapsed between the beginning and end of replicate sampling.

Shoot harvest and seedling viability

Simultaneously with the root tuber harvesting, shoots were separated 25 mm above the rootstock from the root-system and their fresh weight recorded. Shoot dry matter (DM) was recorded after the samples were oven dried at 65°C until constant weight was reached. Shoot-root ratio was calculated by dividing shoot dry matter by fine root dry matter.

Seedling survival was recorded bi-monthly during the rainy seasons of 2013/2014 and 2014/2015, and survival probability per treatment was calculated with the Kaplan-Meier estimator (*Mertens et al.*, 2017). We interlinked the survival probability per treatment with root tuber volume and root tuber fresh weight in order to analyze potential dependence of these parameters.

Soil physical parameters

In order to identify the interdependence of the root system of *S. tuberosa* and soil physical properties, we adopted soil water content data as well as data on bulk density (ρ_b), total porosity (Φ), air capacity (AC), water content at permanent wilting point (θ_{pwp}), and water content at field capacity (θ_{fc}) of the planting holes from the study of Mertens *et al.* (2017). We used the monthly mean water content per treatment, assessed weekly using a frequency domain reflectometry (FDR) soil probe (PR2 by Delta-T Devices Ltd., Cambridge, UK), to calculate the mean water content per treatment for the entire experimental period. The parameters ρ_b, Φ, θ_{pwp}, θ_{fc} were determined in undisturbed 100 cm^3 soil samples taken at 0 – 30 cm and 30 – 60 cm soil depths. Both hydrological parameters were measured using a ceramic plate extractor at suction rates of -0.033 MPa and -1.5 MPa, respectively. Bulk density (ρ_b) and Φ were calculated according to Embrapa guidelines (*Donagema et al.*, 2011). Air capacity (AC) was computed by subtracting θ_{fc} from Φ.

Statistical analyses

Statistical analyses were performed using R, expanded with agricolae and asbio packages, run from the interface software RStudio (*Aho*, 2016; *Mendiburu*, 2014; *R Core Team*, 2016; *RStudio*

Team, 2016). Effects of soil depth, treatment and depth × treatment interaction on RLD and fine root DM were assessed using two-way ANOVA with repeated measures per planting hole. Treatment effects on shoot dry matter and root-shoot ratio were assessed using a one-way ANOVA. Treatment effects on tuber volume, and fresh weight were assessed through an ANCOVA, with elapsed time since root tuber harvest had begun being used as a covariate. All data were log-transformed prior ANOVA or ANCOVA in order to get normality of residues and homoscedasticity. To identify significant differences between treatments, Tukey's HSD post-hoc test (α = 0.05) was performed. To identify significant secondary effects of additional mineral fertilizer application and/or biochar application when planting holes were treated with manure or clay substrate, a priori orthogonal contrasts were used. These orthogonal contrasts were then utilized to compare the clay substrate group with the manure group – with/without biochar and with/without mineral fertilizer – with regard to the growth response of root tubers, fine root parameters (0 – 60 cm) and shoot-root ratio as specified in Table 5.2. The interrelations between root tubers and fine root parameters, between fine root parameters and soil physical parameters, as well as between root tubers and seedling vigor data were analyzed using linear models and calculating their Pearson product-moment correlation coefficient (PPMCC).

Table 5.2: Orthogonal contrasts to compare the groups with clay and with goat manure, additionally nourished with biochar and/or mineral fertilizer.

Considered Treatments	Goat manure or Clay substrate	Goat manure w/ or w/o min. fertilizer	Goat manure & min. fertilizer w/ or w/o biochar	Goat manure w/o min. fertilizer w/ or w/o biochar	Clay substrate w/ or w/o min. fertilizer	Clay substrate & min. fertilizer w/ or w/o biochar	Clay substrate w/o min. fertilizer w/ or w/o biochar
BiMaMi	1	1	1	0	0	0	0
BioMan	1	-1	0	1	0	0	0
Clay	-1	0	0	0	-1	0	1
ClayBio	-1	0	0	0	-1	0	-1
ClayMin	-1	0	0	0	1	-1	0
ClBioMin	-1	0	0	0	1	1	0
ManMin	1	1	-1	0	0	0	0
Manure	1	-1	0	-1	0	0	0

5.3 Results

Description of the root architecture

The coarse root system of three-year-old seedlings, grown in undisturbed soils (Con1), had horizontal and vertical extents of 19.9 ± 10.6 cm and 47.8 ± 17.6 cm (mean ± standard deviation), respectively, and the maximum recorded rooting depth of the coarse root system was 63.0 cm (Figure 5.2). The number of coarse roots per plant was 8 ± 5 with a mean accumulated length of 125.8 ± 84.8 cm. The number of root tubers ranged from 2 to 4 per seedling. Soil depth had no significant effect on the root length density (RLD) or fine root DM of the three-year-old seedlings (Table 5.3).

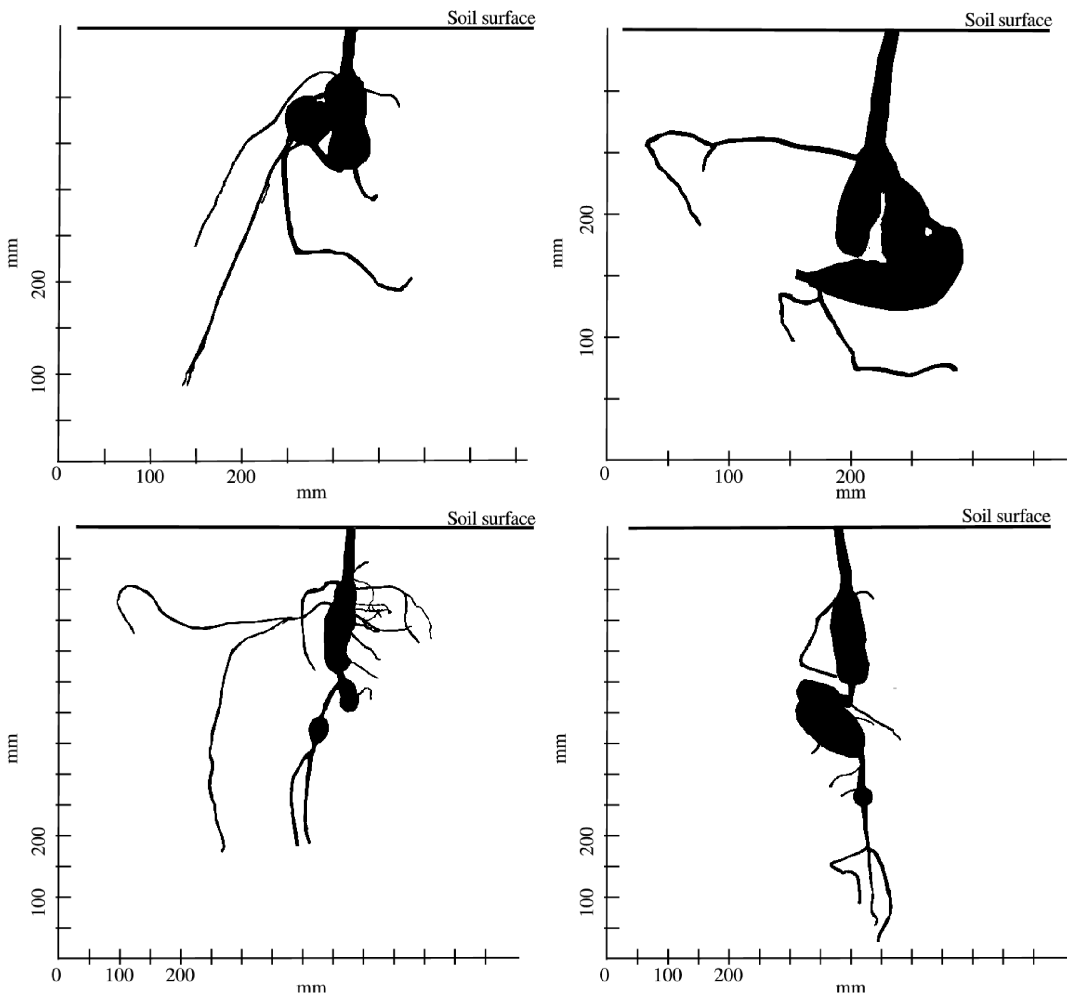

Figure 5.2: Silhouettes of the coarse root system including root tubers of the three-year-old *S. tuberosa* seedlings of Control 1 grown in undisturbed soil.

Table 5.3: Mean RLD and fine root dry matter in different soil depth ± standard deviation (SD) of three-year-old *S. tuberosa* seedlings.

Soil depth (cm)	RLD ± SD (cm cm^{-3})	Fine root dry matter ± SD (g)
0 – 30	0.68 ± 0.81	0.23 ± 0.30
30 – 60	0.19 ± 0.21	0.06 ± 0.06

Response of fine roots, shoots, shoot-root ratio, and root tubers to soil amendments

Root length density (RLD) ranged from 0.66 ± 0.83 cm cm^{-3} (mean ± SD) for Con1 to 0.08 ± 0.07 cm cm^{-3} for BiMaMi treatment, but treatments, soil depth, and their interaction had no significant effect on RLD. Treatments had a significant effect on fine root DM, whereas depth and the interaction between depth and treatments were not significant (Table 5.4). Fine root DM was lowest for the BiMaMi treatment and, according to a Tukey test, differed significantly from the values for Con1 and the ClBioMi, ClayBio, and Clay treatments (Figure 5.3). Based on comparison with the orthogonal contrasts, manure significantly reduced fine root DM ($p = 0.001$), but additional enrichment with biochar and/or mineral fertilizer had no significant effect.

Table 5.4: Output of two-way repeated measures ANOVA of root length density (RLD) and fine root dry matter (Fine root DM) of three-year old *S. tuberosa* seedlings. *p*-values below 0.05 indicate significance (printed in bold).

		RLD		Fine root DM	
	dF	F value	*p* value	F value	*p* value
Treatment	12	1.691	0.096	2.147	**0.029**
Soil depth	1	0.244	0.624	1.113	0.296
Treatment × soil depth	12	0.768	0.679	0.504	0.903

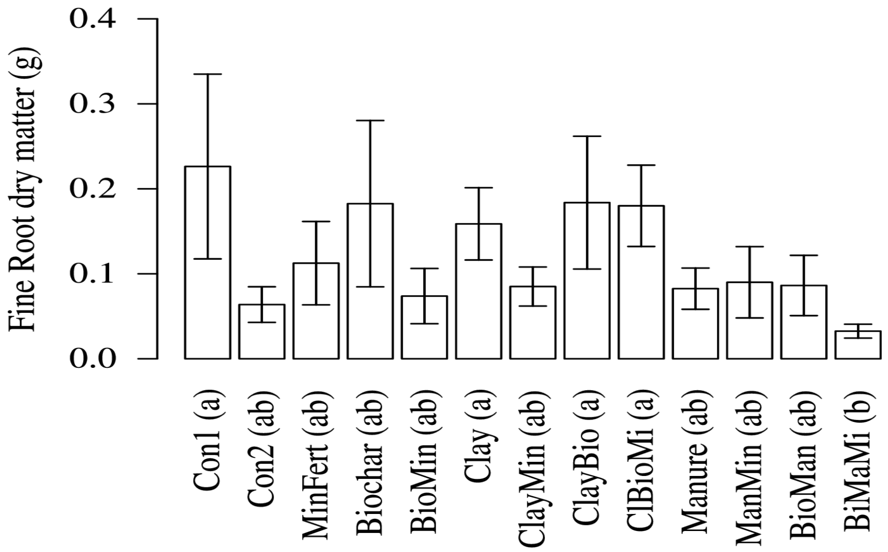

Figure 5.3: Median of fine root dry matter of *S. tuberosa* seedlings (0 – 30 cm). Error bars indicate median absolute deviation (MAD) (n = 8), treatments labeled with the same letters are not significantly different (α = 0.05) by Tukey HSD test.

Treatments had no significant effect on shoot DM, though it did have significant effects on seedling shoot-root ratio, the quotient of shoot DM and fine root DM (Table 5.5). According to the Tukey HSD post-hoc test, BiMaMi was significantly different from Con1, and ClBioMi. Treatments containing manure in the backfill mix showed the highest shoot-root ratio (Figure 5.4), which is backed up by the orthogonal contrasts, where a positive significant response of shoot-root ratio to manure was identified ($p = 0.001$).

Table 5.5: Output of one-way ANOVA of shoot dry matter (Shoot DM) and shoot-root ratio of three-year old *S. tuberosa* seedlings. *p*-values below 0.05 indicate significance (printed in bold).

		Shoot DM		Shoot-root ratio	
	dF	F value	*p* value	F value	*p* value
Treatment	12	0.804	0.644	2.568	**0.013**

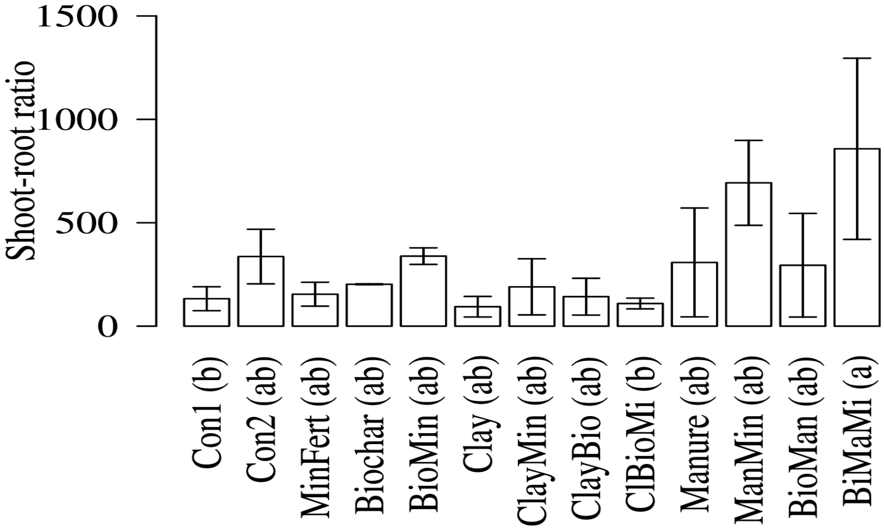

Figure 5.4: Median Median of shoot-root ratio of *S. tuberosa* seedlings. Error bars indicate MAD (n = 4), treatments labeled with the same letters are not significantly different (α = 0.05) by Tukey HSD test.

Treatments had a significant effect on mean root tuber fresh weight, but not on mean root tuber volume per tree (Table 5.6). The covariate of elapsed time following tuber harvest had also a significant effect on both parameters. Sole manure addition tended to increase fresh weight, although no significant differences between single treatments were reported by the Tukey test (Figure 5.5). Comparison of the groups containing clay substrate or manure with the orthogonal contrasts identified a significant effect of manure on tuber fresh weight (p = 0.030). Meanwhile, within the manure orthogonal contrast group, mineral fertilizer had a significant negative effect on tuber fresh weight (p = 0.039).

Table 5.6: Output of ANCOVA of root tuber volume and root tuber fresh weight (Tuber FW) of three-year old *S. tuberosa* seedlings. *p*-values below 0.05 indicate significance (printed in bold).

		Tuber volume		Tuber FW	
	dF	F value	*p* value	F value	*p* value
Treatment	12	1.989	0.053	2.216	**0.031**
Elapsed time	1	6.556	**0.015**	7.138	**0.011**

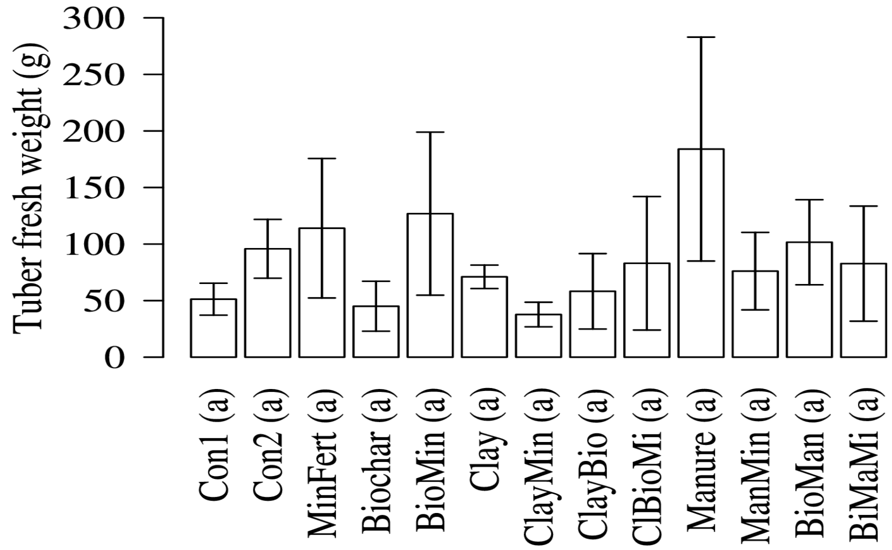

Figure 5.5: Median of root tuber fresh weight per *S. tuberosa* seedling. Error bars indicate MAD (n = 4), treatments labeled with the same letter are not significantly different (α = 0.05) by Tukey HSD test.

For RLD and fine root DM within the planting hole (0 – 60 cm), root tuber fresh weight and volume, shoot DM, and shoot-root ratio of the three-year-old *S. tuberosa* seedlings the Tukey test did not report significant difference between sole biochar, clay substrate, or mineral fertilizer compared with the controls.

Interrelations of plant compartment growth and their relation to soil physical parameters

Among all treatments, root tuber volume as well as root tuber fresh weight showed a weak negative correlation with RLD as well as with fine root DM (0 – 60 cm) (Table 5.7). Investigating the decisive parameters affecting the RLD and fine root DM, a weak negative correlation between mean volumetric soil water content in the planting hole and RLD and fine root DM (0 – 60 cm) was found, both of which also exhibits a weak negative correlation with total porosity (Φ) and with bulk density (ρ_b). However, no correlation was observed between either RLD or fine root DM and air capacity (AC), water content at permanent wilting point (θ_{pwp}) or water content at field capacity (θ_{fc}). Root tuber volume as well as root tuber fresh weight did exhibit a weak significant negative correlation with ρ_b and a weak correlation with Φ, though no correlations between soil hydrological parameters and root tuber volume or fresh weight were observed.

There was no significant correlation between root tuber fresh weight ($p = 0.415$), or root tuber volume ($p = 0.486$) and survival of the *S. tuberosa* seedlings.

Table 5.7: Pearson product-moment correlation coefficient (PPMCC) and *p*-values of significant correlations.

Correlation	PPMCC	*p*-value
Root tuber volume ~ RLD	-0.25	0.010
Root tuber volume ~ Fine root dry matter	-0.34	0.015
Root tuber volume ~ ρ_b	-0.31	0.026
Root tuber volume ~ Φ	0.28	0.047
Root tuber fresh weight ~ RLD	-0.23	0.018
Root tuber fresh weight ~ Fine root dry matter	-0.33	0.016
Root tuber fresh weight ~ ρ_b	-0.29	0.037
Root tuber fresh weight ~ Φ	0.27	0.050
RLD~ Soil water content	-0.24	0.012
RLD ~ Φ	-0.37	0.001
RLD ~ ρ_b	0.36	0.009
Fine root dry matter ~ Soil water content	-0.27	0.049
Fine root dry matter ~ Φ	-0.36	0.008
Fine root dry matter ~ ρ_b	0.32	0.020
Shoot-root ratio ~ Soil water content	0.50	< 0.001

Verbally description of the strength of the correlation suggested by Evans (1996): 0.00 – 0.19 "very weak"; 0.20 – 0.39 "weak"; 0.40 – 0.59 "moderate"; 0.60 – 0.79 "strong", 0.80 – 1.00 "very strong".

5.4 Discussion

The aim of the experiment was to examine the root system of *S. tuberosa* and its response to amelioration in order to provide an initial basis for a scientifically guided cropping system for *S. tuberosa*. The results revealed a negative effect of manure on fine root DM, presumably due to the increased soil water content in planting holes treated with manure. Simultaneously, manure reduced soil bulk density, which affected tuber growth positively. Compared to the controls, biochar, and clay substrate application remained ineffective in our experiment.

Coarse root architecture

The three-year-old *S. tuberosa* seedlings in our study featured a tap root with a dominating downward elongation. Consulting results from Cavalcanti *et al.* (2010) revealed that the maximal horizontal and vertical extent of the coarse roots in our study were less compared to their seedlings of the same age. We also did not observe a shift towards dominant horizontal elongation of the coarse root system two years after planting that they reported. It seems the transition of the coarse root system and its development was delayed in our experiment, since also the range in number of root tubers found under our three-year-old experimental plants was three times less than reported by Cavalcanti *et al.* (2010). A reason for the lower coarse roots growth and development might be different residence times for the seedlings in grow-bags. The plant material used in our study remained in small grow-bags (9.5 l) for the first year after germination until transplanting, whereas Cavalcanti *et al.* (2010) transplanted the seedlings six months after germination. All silhouettes of the root systems of Con1 plants show evidence of disturbed vertical elongation, presumably caused by this long residence time in small grow-bags (Figure 5.2). Akpo *et al.* (2014) have illustrated the negative effect of small grow-bags on the seedling performance and development of oil palms (*Elaeis guineensis* Jacq.) after a brief residence time of four months. Therefore, we now suggest that the residence time of *S. tuberosa* seedlings in grow-bags in a plant nursery should be as brief as possible, and spacious grow-bags should be used to avoid lasting negative impact on seedling root development.

Plant-soil amendment interaction

Previous studies showed that, in water-limited environments without additional irrigation, soil water is the key factor controlling fine root growth, characteristics and distribution. Generally, a positive correlation between fine root biomass, or root length and soil water content has been observed (*West et al.*, 2004; *Wilcox et al.*, 2004; *Zhou and Shangguan*, 2006). In our study, significant weak negative correlations between soil water content and RLD and fine root DM were observed (Table 5.7). This concurs with the findings of Cheng *et al.* (2006), who reported a negative correlation between fine root biomass and soil moisture. The manure orthogonal group was found to be the decisive soil amendment group, negatively affecting the fine root DM of *S. tuberosa*. Manure also significantly increased soil water content within planting holes in the same field experiment (*Mertens et al.*, 2017). The investment of plants in fine root production is only maintained until the marginal revenue from increased production is equal to the marginal cost (*Bloom et al.*, 1985), which implies that plants invest resources efficiently in water and nutrient uptake. The negative correlation between RLD and fine root DM with soil water content may be result from the “low nutrient” and “low water” adaptation of the largely undomesticated plant material used (*Mertens et al.*, 2017; *Reich*, 2014) in combination with a better supply of nutrients via mass-flow and diffusion in wetter soils, due to thicker water film around soil particles (*Barber*, 1962; *Halvorson*, 2006). In contrast, Cheng *et al.* (2006) concluded that excessive soil moisture may cause a negative correlation between fine root biomass and soil water content if, simultaneously, nutrient concentrations in the given soil are meager. Our results suggest that, under a soil water surplus, *S. tuberosa* reduces its fine root growth, since mass-flow and diffusion sufficiently deliver nutrients and water, and the seedlings will gain no marginal revenue from tapping larger soil volumes. Its adaptation to infertile soils and limited water availability may be the reason that root growth did not increase under luxury soil conditions, which is a trait common to wild plants from low-nutrient environments (*Chapin*, 1980).

Manure addition increased the shoot-root ratio as a function of increased soil water content (Figure 5.4, Table 5.7). In reverse, this observation is in line with higher investment of trees into root compared to shoot biomass under drought conditions (*Brunner et al.*, 2015).

Root tubers of *S. tuberosa* responded to the manure treatment with significantly increased fresh weight but, in contrast to fine root biomass, this did not correlate with soil water content. Soil bulk density and total porosity in planting holes were also significantly affected by manure application (*Mertens et al.*, 2017), and both revealed correlations with root tuber volume and fresh weight. Consequently, we assume that root tuber growth in our experiment was primarily affected by soil compaction, as a similar effect was reported for the bulky roots of *Beta vulgaris* cv Bravo (*Hoffmann and Jungk*, 1995). When planting holes with manure were additionally enriched with mineral fertilizer, the positive effect of reduced bulk density and increased total porosity on root tubers was suspended – an observation which is uncommon for plants adapted to low-resource environments. An increase in root tuber volume and fresh weight was expected, since slow-growing wild plants adapted to low-resource environments are thought to invest in the production of storage organs under nutrient surplus (*Chapin*, 1980; *Chapin et al.*, 1990). In contrast, however, *S. tuberosa* formed smaller storage organs under favorable soil physical, and nutrient-rich soil conditions.

Effect of root tuber growth on seedling vigor

It is suspected that the root tubers of *S. tuberosa* enable its survival during the dry season and allow flowering before onset of the rainy season. It is assumed that survival and flowering are made possible through tree expenditure of resources stored in the root tubers from the previous rainy season (*Lima Filho*, 2007, 2001). In our experiment, a significant negative effect of the covariate time elapsed during tuber harvest on tuber fresh weight and tuber volume was observed, likely indicating a partial depletion of stored water during the two weeks of tuber harvest without irrigation. Therefore the tubers of *S. tuberosa* seedlings also have a crucial function in bypassing short dry periods during their growing period.

There was, however, no statistical evidence from our experiment that heavier root tubers, meaning increased storage, facilitate survival of *S. tuberosa*.

Importance of experimental design

The recorded root architecture of the three-year-old *S. tuberosa* seedlings grown in undisturbed soil in our study may differ from seedlings grown under natural conditions, as the experimental design and methods may have caused a bias leading to root architecture alteration as well as interference with the plant's physiology.

Our irrigation method – water applied weekly proximate to the rootstock, combined with a high infiltration rate for the untreated soil of 389 ± 51 mm h^{-1} (mean ± SD) (*Mertens et al.*, 2017) – led to a wet zone of a relatively small horizontal extent within the surrounding dry soil. Due to regular irrigation, this spatially limited wet zone dominated in time over evenly wetted soil conditions following natural precipitation. This may have affected the horizontal shallow growth of coarse roots that is characteristic of *S. tuberosa* (*Cavalcanti*, 2008; *Cavalcanti et al.*, 2010), since horizontal growth of coarse roots in order to increase water uptake from greater soil volume was not stimulated in our experiment. Hydrotropism of coarse tree roots has also been reported for *Olea europaea* L. and *Prosopis flexuosa* D.C. *(Guevara et al.*, 2010; *Polverigiani et al.*, 2011). According to Polverigiani *et al.* (2011), the hydrotropism of coarse tree roots is unexpected, since they have no function in nutrient and water absorption. Consequently, irrigation quantity as well as irrigation technique, appears to be a crucial factor affecting the root architecture of *S. tuberosa* and, thus, has to be calibrated carefully in order to avoid unnatural alteration of coarse root growth for studies carried out on this species.

In nearly all treatments, weekly irrigation led to soil water content constantly above the permanent wilting point, thus, seedling dieback was not primarily caused by drought stress (*Mertens et al.*, 2017). This could explain the lack of interrelation found between root tuber fresh weight and survival. The lack of drought stress during the experiment may also have been a reason for the lower number of root tubers compared to previous *S. tuberosa* studies. Drought stress has been shown in two studies to be the trigger for two tree species to invest in root storage organs, as stressed seedlings have contained more carbon assimilates in their storage organs compared with the controls (*Arndt et al.*, 2001; *Galvez et al.*, 2013). As this trigger was absent in our experiment tuber formation was likely not stimulated. Beside the interference due to weekly irrigation, the newly developed pin-frame method used for spatial fixation of the coarse roots was also identified as a source of bias, as the grid spacing of 10 cm in the topsoil potentially led to a measuring error of 10 cm regarding horizontal root extent in our study. However, even when adding a maximal error of 10 cm to our results, the observed horizontal extent of the coarse roots in our experiment was still five times less than that reported by Cavalcanti *et al.* (2010). Although the spacing of 10 cm appeared effectual during preliminary testing, when using the pin-frame method in the future, we suggest reducing the spacing to 5 cm in order to minimize bias. Such spacing was recommended by Schuurman and Goedewaagen (1971) for homorhizy field crops and could be more appropriate for the root system of *S. tuberosa* seedlings than 10 cm.

Significant treatment effects on the root system of *S. tuberosa* were observed in our experiment, resulting from manure addition. Since Mertens *et al.* (2017) did not report any significant effect from biochar or clay substrate on soil physical parameters or shoot growth, the absence of a significant effect on the root system was not unexpected. We thus argue that the observed treatment effects of manure are temporary and will dissipate with time. Under the experimental conditions, the mineralization of manure was rapid and 93 % of the initial carbon stock was lost within the first 16 months (*Mertens et al.*, 2017). Therefore, a long-term treatment effect remains uncertain. Treatment effects of biochar or clay substrate cannot be excluded in general and should be tested again. For this, we recommend an increased application rate for clay substrate and the use of a more porous and hydrophilic biochar (compare *Mertens et al.*, 2017).

5.5 Conclusion

To our knowledge this is the first study reporting on the root system development of *S. tuberosa* during its transition from the seedling to sapling stage. Our study provides novel information about the root system of *S. tuberosa* and its responses to soil management. Unusual for arid climates, the fine root DM of *S. tuberosa* was reduced with increasing soil water content in planting holes. Still, the different shoot-root ratios of the three-year-old seedlings suggest that *S. tuberosa* increases fine root DM under drier soil conditions, in order to increase water uptake and interception. Amelioration with goat manure increased soil water content, which impeded fine root growth, whereas root tuber growth responded positively to reduced soil bulk density due to this addition. Yet, simultaneous supply of mineral fertilizer, at doses considered optimal for shoot growth, nullified the positive growth effect of reduced soil bulk density. Amelioration with clay substrate or biochar at the given rates did not affect fine root growth or tuber development compared with the control groups. Soil management that reduces soil bulk density should be a focus when *S. tuberosa* is planted under rain-fed conditions, in order to support root tuber growth. We assume that, at the seedling stage, water storage within the root tuber is momentary, as there was no statistical evidence for a relationship between seedling survival and root tuber volume.

Since our study was conducted with rather inhomogeneous and largely undomesticated plant material, it is possible, that other treatment effects remained imperceptible. Therefore, progress in the cloning of *S. tuberosa* is indispensable in order to further evaluate and possibly verify our results. With increasing domestication or breeding of *S. tuberosa*, the observed obstructive effects that appear to be due to soil management need to be re-examined as well. Lastly, the relevance of water storage in the root tuber needs to be studied in older saplings and adult individuals.

Acknowledgement

This work was supported by the German-Brazilian joint research project INNOVATE (Interplay among multiple uses of water reservoirs via innovative coupling of aquatic and terrestrial ecosystems). The project is funded by the German Federal Ministry of Education and Research (BMBF) under project number 01LL0904B. The first author would also like to thank for support by the fiat panis foundation Ulm, Germany. Further, we are grateful for the support of Dr. Francisco Pinheiro de Araújo and Dr. Magnus Dall Igna Deon from Embrapa Semiárido (Embrapa-CPATSA) for the provision of the plant material and the facility for processing the fine root samples.

6. General Discussion

Due to the cumulative nature of this dissertation, results and methods of each publication have been concluded and/or discussed in its respective chapter. Therefore, the following chapter will discuss the hypotheses presented in Chapter 1.2.

6.1 *Spondias tuberosa*, a non-threatened tree from the scientific perspective but at risk to become extinct

The conservation status of *S. tuberosa* as well as information about the threats it faces crucial knowledge in order to sustainably manage the tree, and its resources. As Chapter 2 concluded, *S. tuberosa* is a scientifically neglected species, causing the dilemma of its conservation status. The Red List of Threatened Species provided by the IUCN, the most authoritative system for categorizing an extinction risk (Chapter 3), requires research efforts to effectively assess the risk of extinction of a species. Particularly, scientific analyses of the population structure, size, and dynamics as well as the area of occupancy of a species are required. In the case of *S. tuberosa* this scientific groundwork is missing entirely and *S. tuberosa* cannot be considered threatened on a scientific basis. Concerns about its conservation status were broached only by non-scientific media (Chapter 3.2), although scientific knowledge about natural and man-made threats to *S. tuberosa* are available.

a) <u>*S. tuberosa* suffers a hampered natural regeneration and its natural population is at risk to become extinct.</u>

Available literature on *S. tuberosa* suggests a hampered generative regeneration resulting from seed infestation, lack of dispersers, and browsing pressure. This leads to the absence of seedlings and juvenile individuals of *S. tuberosa* within the Caatinga biome. As reported in Chapter 3, in SDTFs the generative regeneration is less important than re-sprouting for forest recovery after disturbance including man-made, locally limited disturbances, such as slash and burn. The benefit of re-sprouting is to shortcut forest recovery bypassing the bottleneck of the frail seedling stage (reviewed in *Vieira and Scariot*, 2006). According to Aitken *et al.* (2008), under changing climatic conditions, however, tree populations have three possible fates under this large-scale disturbance: (1) migration to track their ecological niches spatially, (2) adaptation to new conditions in the current location, or (3) extinction. Since changing vegetation cover in the Caatinga is expected and large-scale desertification is likely (*Salazar et al.*, 2007), the *S. tuberosa* population will experience one of these fates.

Migration of tree populations is slow, less than 100 m per year, and effectiveness increasing long distance seed dispersal is rare (*Aitken et al.*, 2008). To track its niche under doubling CO_2 emissions within the next 70 years, species require migration rates of more than 1000 m per year in tropical biomes (*Malcolm et al.*, 2002). The *S. tuberosa* population, with a restricted natural dispersal (Chapter 3.3), cannot fulfill this requirement for an increased migration rate. Thus, the *S. tuberosa* population cannot track its shifting ecological niche. Alternatively, *S. tuberosa* could adapt to the new conditions at the current location by mutation or changes in epigenetics[♦](*Aitken et al.*, 2008). Such an adaptation of trees is facilitated by high levels of genetic diversity, large population sizes, active gene flow and can take place in less than five generations (*Oddou-Muratorio and Davi*, 2014). However, without generative regeneration helping to speed up adaptation and fortify beneficial mutation (*McDonald et al.*, 2016), active gene flow is not given. Therefore, the adaptation of the *S. tuberosa* population to new conditions in the current location will hardly take place. Considering the constraints on migration and adaptation, the fate that appears most likely for *S. tuberosa* population is extinction.

From a scientific perspective, *S. tuberosa* still can not be considered threatened because further information is needed for a Red List of Threatened Species threat assessment. At the same time it is scientifically known that the *S. tuberosa* population faces a high risk of extinction, due to its inability to migrate or adapt.

If *S. tuberosa* is extinct, an important contribution to Caatinga dwellers livelihood is lost, moreover two promising benefits with global significance would be lost too. First, *S. tuberosa* seeds are a source of high quality seed oil for nutritive or industrial purpose (Chapter 2.6). Production of seed oil would not create competition for arable land between food and vegetable oil production, since marginal sites planted with *S. tuberosa* are able to simultaneously provide feedstock for food and oil production. Competition for arable land between food production and vegetable oil or biofuels is connected with negative environmental impacts of global significance

♦Epigenetics is defined by Bird (2007) as: “The structural adaptation of chromosomal regions so as to register, signal or perpetuate altered activity states”. A changed gen expression, that can not be explained by changes in the DNA sequence such as loss of biodiversity, and increased greenhouse gas emissions, which result from further clearing of natural vegetation (*Searchinger et al.*, 2008; *Tilman et al.*, 2009). Second, if the rutin and quercetin extracted from *S. tuberosa* leaves function as an anti-viral agent to fight the dengue serotype DENV 2 gets affirmed, *S. tuberosa* could contribute to fight and control dengue fever (Chapter 2.7). A mosquito-born disease, that is abundant throughout the entire tropics and affects half the world's population (*Tolle*, 2009).

6.2 *In-situ* evaluation of the potential of biochar, clay substrate, and goat manure for amelioration in semiarid tropics

Drylands are susceptible to soil degradation due to natural process, climate change and human action, with desertification as the ultimate consequence (*Katyal and Vlek*, 2000). The same authors stated, that soil quality is antonymous to soil degradation. Therefore, soil management that stabilized and improved soil quality is able to mitigate desertification. The use of the soil conditioners biochar, clay substrate, and goat manure aim to maintain or improve soil quality respectively soil fertility. Consequently they are resources to fight desertification in semiarid regions. A controversy surrounds the effectiveness of biochar as a soil fertility improving soil conditioner and emphasizes the need for *in-situ* experiments to assess their effectiveness under semiarid conditions. The effectiveness of biochar in improving soil hydrological parameters was proven in pot experiments but may not apply to field experiments, since the soil physical parameters assessed in pot experiments are artifacts of soil sieving and packing and do not resemble *in-situ* soils (*Hardie et al.*, 2014). In three recent field experiments on sandy soils biochar was found to be ineffective and did not change soil hydrological parameters (*Hardie et al.*, 2014; *Jeffery et al.*, 2015; *Jones et al.*, 2012). When linking improved soil quality with increased crop productivity, the meta-analysis of Jeffery *et al.* (2011) underlines the consideration of Hardie *et al.* (2014). Their meta-analysis of 14 publications on biochar revealed that pot experiments increased the biochar-mediated crop productivity three times more than in field experiments (*Jeffery et al.*, 2011).

b) Coarse-textured sandy soil exhibits (i) an increased field capacity (FC) as well as available water capacity (AWC), and (ii) an extended period in which the soil moisture exceeds the permanent wilting point (PWP) due to amelioration with biochar, clay-substrate or goat manure.

(i) The application of biochar and clay substrate did not improve soil quality. Compared with the controls, no change in FC nor AWC was observed after the biochar and clay substrate addition. As discussed in Chapter 4.4 the application rate of the clay substrate was too little, since the experimental soil was poor in fine particles (< 0.02 mm). The application rate was identified as the single cause since the smectite content of utilized substrate and the initial clay content of the experimental soil, were satisfactory.

Due to its porous character, biochar may improve soil hydrological parameters through contribution of new pores in its matrix (*Atkinson et al.*, 2010). However, these new pores are presumably small and bind water, after hydrophobicity was overcome, at suction between -10 and -1,000 MPa (*Verheijen et al.*, 2009), thus below the suction at PWP, and additional stored water is not plant available. Consequently, the contribution of biochar to meso- and macroporosity due to its ability to increase soil aggregate stability is important for soil hydrological parameters, but continues to be poorly understood (*Sohi et al.*, 2009). In order to improve aggregation, biochar needs to interact with soil organic matter or charged minerals. The low C content of 0.2 % and the low CEC of 0.9 $mmol_c\ kg^{-1}$ indicate that the experimental soil lacks both, organic matter and charged minerals, and an improved aggregation of the soil due to biochar application is unlikely. Besides the hydrophilic character and little internal pyrogenic nanoporosity of the biochar used (Chapter 4.4), the lack of aggregation resulted in no biochar-mediated soil improvement of the experimental sandy soil.

Goat manure at given applications rates seemingly increased soil water content at FC. The increased water content at field capacity was realized by increased water content at PWP and AWC remained unchanged (Chapter 4.3, Table 4.3). Additionally water stored in pores was not plant available as well. The surplus of soil water due to the manure application, however, had a severe impact on the added organic matter in the planting hole itself. Rey *et al.* (2005) observed an increasing mineralization in incubated Mediterranean forest soils with increasing temperature and water content. This interaction explains the high mineralization rate, loss of 93 % of the initial carbon stock within the first 16 months, observed in the manure treatments (Figure 4.3). The constant favorable ambient temperature and soil moisture serve the mineralization in the planting holes. Consequently, under hot semiarid field conditions with additional irrigation, application of manure facilitates its own mineralization and effects of manure application on soil physics are not long-lasting.

(ii) Compared with both controls, none of the treatments was able to prolong the period until soil water content reached the PWP. In contrast, two treatments significantly shortened this period (Table 4.5). The observations may have resulted from the low albedo of the dark soil conditioner and a subsequent higher evaporation especially from the planting holes treated with biochar or manure (*Basso et al.*, 2013; *Dobos*, 2011). The results from Table 4.3 further explain this observation. All treatments exhibited an increased soil water content at PWP when compared to controls. Thus, even with invariant evaporation, the soil conditioners did not prolong period in which the soil moisture exceeded PWP. The conditioners increased the share of water that was not plant available.

Under semiarid field conditions with additional irrigation at given application rates, the soil conditioners biochar, clay substrate, and goat manure cannot be considered resources to mitigate desertification, since no significant soil quality respectively soil fertility improving effects were observed.

6.3 Does amelioration support growth and development of the nondomesticated endemic *Spondias tuberosa?*

The field experiment also attempted *in-situ* to evaluate whether the soil conditioners mentioned above helped the establishment and development of *S. tuberosa* seedlings. Because when *S. tuberosa* is planted for forest recovery, the seedling stage is considered the most critical for its survival (*Cavalcanti et al.*, 2006a).

c) <u>Establishment and development of *S. tuberosa* seedlings improved due to improved AWC and prolonged period in which the soil moisture exceeds the PWP.</u>

Since neither an improved AWC nor a prolonged period in which the soil moisture exceeded the PWP was observed in the experiment, a verification or falsification of this hypothesis is not possible.

d) <u>Fine root growth of *S. tuberosa* is positively affected by improved soil hydrological properties but is hampered by mineral fertilizer applications.</u>

No soil hydrological parameters were significantly altered due to biochar or clay substrate application, therefore the effects of the goat manure application are in focus. The manure addition significantly changed the hydrological parameters, specifically the soil water content at PWP and infiltration rate. In Chapter 5.4, a significant weak negative correlation of soil water content with RLD, and fine root biomass was reported. Per definition, the soil water content at PWP (bond at suction ≥ -1.5 MPa), cannot be recruited by plants and accordingly does not interact with root development. Therefore, the reported negative correlation cannot be explained by the increased soil water content at PWP. Infiltration into the planting hole tended to decelerate with the manure application (Figure 4.2), and the manure application likely also affected the percolation within the planting hole. Presumably, the slower percolating irrigation water caused the significantly higher water content in the planting holes treated with manure in all consecutive months of the experiment, since the measured water content was above the measured field capacity in the manure treatments (Table 4.3, Table 4.4). Following the conclusion of Chapter 4 and Chapter 5 the utilized plant material of *S. tuberosa* is rather nondomesticated and invests resources efficiently in water and nutrient uptake. There are two possible explanations for the negative correlation of soil water content and fine roots. Although the retarded percolating water is moving downwards, it may contribute to nutrient delivery to the fine roots via mass-flow and diffusion. Consequently, *S. tuberosa* is reducing fine root growth due to the sufficient supply of mineral nutrients and water (Compare 5.4). An alternative explanation could be that fine roots are known to be sensitive to hypoxic conditions due to air displaced by water in soil pores (*Armstrong and Drew*, 2002; *Crawford*, 1992). The negative correlation of soil water content and root growth may also indicated indirectly a lack of oxygen supply. In Chapter 4, altered air capacity is reported, however, this parameter is not serviceable do discuss whether hypoxic conditions were present. Since it gives the percentage of macropores, which have an equivalent diameter of ≥ 10 µm (*Rouquerol et al.*, 1994), and a suction of ≤ -0.033 MPa, which are air filled when the soil is totally drained by gravitation. Consulting the values from Table 4.3 and Table 4.4 allow an estimation of the percentage of water filled macropores. When estimated for the Manure treatment using the mean soil water content computed of all means from all consecutive month, the mean field capacity and mean air capacity from all replicates in the 20 cm and 40 cm soil depth shows, that approximately 8 % of the macropores were filled with water and the air capacity of 42 % got reduced to an effective air capacity of 34 %. Cook *et al.* (2013) model a critical air-filled porosity. The threshold at which the oxygen concentration becomes critical to maintain plant growth and rhizosphere processes including nutrient uptake was reported as approximately 15 % for a 20°C ambient temperature and rises to approximately 17 % when the temperature increases to 30°C. With a manure treatment air-filled porosity of 34 %, hypoxic conditions were unlikely the root growth impedance in the *S. tuberosa* field experiment and the reduced root growth was more likely caused by better water and nutrient supply.

The results of this first study on root response of *S. tuberosa* to amelioration show that improved soil water regime impedes the growth of fine roots of *S. tuberosa.* Instead of responding to improved soil quality with increasing root growth, the available plant material of *S. tuberosa* response was typical of nondomesticated plants adapted to water limited sites (*Chapin*, 1980). The luxury conditions of the soils allowed *S. tuberosa* to develop a smaller root system in order to meet its water and nutrient needs. A less developed root system, however, may weaken the drought adaptation of *S. tuberosa.*

e) <u>Increased soil water content promote root tuber growth of *S. tuberosa*.</u>

Since the lack of growth response of shoot and roots to improved soil quality indicated, that the plant material of *S. tuberosa* is nondomesticated, an improved growth of the storage organs as a response to the increased soil water content was expected (*Chapin et al.*, 1990). However, the root tubers of *S. tuberosa,* a storage organ for water, minerals, and organic solutes, did not respond with increased growth to increased soil water content. The continuous supply of water in the experiment could be the reason the tree did not invest in storage organs, although, the results showed no statistical evidence for a negative interdependency of tuber parameters and soil water content. Without being exposed to lasting drought stress, there was no marginal revenue of an enlarged storage, which is produced under discontinuous water supply and rain-fed conditions.

Instead of responding to increased soil water content, the root tuber growth of *S. tuberosa* appeared to be sensitive towards compacted soils. The reduced soil density within the manure treatments (Table 4.2) correlated positively with the tuber volume and tuber fresh weight (Table 5.4).

Hence, amelioration that reduces soil bulk density helps *S. tuberosa* to fortify its drought adaptation with bigger and heavier root tubers.

7. Final Remarks

This study aimed to develop the first scientific backed methodology to plant *S. tuberosa* on degraded Caatinga sites with the aid of low-tech measures. The results of the study do not provide a consummate guidance, attributed to the unique plant material *S. tuberosa*. Presumably, due to its rather undomesticated character, management efforts remained ineffective or even hampered its development. Genetically identical clones or hybrids of *S. tuberosa* are not yet available, which also constrained the field experiment because distinct treatment effects remained imperceptible. Nevertheless, this study provides valuable information and results in order to proceed with *S. tuberosa* research as well as contributing to land management strategies on marginal sandy soils under semiarid climates.

This work compiled available relevant literature on *S. tuberosa* and should be used as a base for further research, since it helps to identify urgent research needs. The literature or lack thereof highlight the need for a thorough population study and a protection program for *S. tuberosa*. Otherwise, the important and sacred tree may become extinct. In order to achieve more accurate results in studies about its physiology or growth, progress in *S. tuberosa* cloning is inevitable. Due to its long generation period, four to ten years until the first flower, and its self-incompatible character, cloning should be pursued in order to produce homogeneous plant material. The characteristics of its sexual reproduction make selective breeding, hybrid breeding, and breeding via outcrossing, or via heterosis not applicable for *S. tuberosa* propagation.

The results from Chapter 4 show that the survival and growth of available plant material after transplanting is independent of soil management. This attribute makes *S. tuberosa* an interesting species for reforestation or extensive farmed orchards in the Caatinga without significant amelioration. Chapter 5 revealed that soil quality improving soil management impedes adaptation of *S. tuberosa* to its water and nutrient limited biome.

The *in-situ* evaluation of the three soil conditioner demonstrated the difficulties in modifying the important mesoporosity of soils in oder to improve the available water capacity. Only the ineffective micropores showed a significant volumetric increase as a result of amelioration. The lack of field results after amelioration could simply be a quantity effect, as was the case for clay substrate (Chapter 4). Therefore, the ability of clay-substrate to improve the soil quality needs to be re-examined at higher applications rates. The results of this study suggest that biochar cannot be seen as a soil conditioner affecting soil physical parameters *in-situ.* But consulting preliminary results of Beusch and Kaupenjohann (2015) revealed that biochar is an effective soil conditioner in order to increase nutrient retention of the experimental Arenosol under field conditions as well as in a batch experiment. The observed fast mineralization of the additional organic matter under given conditions was remarkable (Chapter 4) and should be investigated further. First studies are available describing the organic matter turn over and the influence of land use and grazing on soil carbon stocks (*Schulz et al.*, 2016; *Tiessen et al.*, 1998; *Wick and Tiessen*, 2008). In order to gain more profound knowledge of the carbon-cycle in the Caatinga, further *in-situ* experiments are recommended. For instance “litter-bag” experiment that considers different sources of organic matter as well as different moisture regimes of the soil.

8. References

Abdel-Nasser, G., Al-Omran, A.M., Falatah, A.M., Sheta, A.S., Al-Harbi, A.R. (2007): Impact of Natural Conditioners on Water Retention, Infiltration and Evaporation Characteristics of Sandy Soil. *J. Appl. Sci.* 7, 1699–1708.

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G. (2013): Impact of Biochar and Hydrochar Addition on Water Retention and Water Repellency of Sandy Soil. *Geoderma* 202–203, 183–191.

Adams, H.D., Guardiola-Claramonte, M., Barron-Gafford, G.A., Villegas, J.C., Breshears, D.D., Zou, C.B., Troch, P.A., Huxman, T.E. (2009): Temperature Sensitivity of Drought-Induced Tree Mortality Portends Increased Regional Die-Off Under Global-Change-Type Drought. *Proc. Natl. Acad. Sci.* 106, 7063–7066.

Aho, K. (2016): asbio: A Collection of Statistical Tools for Biologists.

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., Curtis-McLane, S. (2008): Adaptation, Migration or Extirpation: Climate Change Outcomes for Tree Populations. *Evol. Appl.* 1, 95–111.

Akpo, E., Stomph, T.J., Kossou, D.K., Omore, A.O., Struik, P.C. (2014): Effects of Nursery Management Practices on Morphological Quality Attributes of Tree Seedlings at Planting: The Case of Oil Palm (*Elaeis Guineensis* Jacq.). *For. Ecol. Manag.* 324, 28–36.

Albuquerqe, S.G. de, Bandeira, G.R.L. (1995): Effect of Thinning and Slashing on Forage Phytomass from a Caatinga of Petrolina, Pernambuco, Brazil. *Pesqui. Agropecu. Bras.* 30, 885–891.

Albuquerque, S.G. de (1999): Caatinga Vegetation Dynamics Under Various Grazing Intensities by Steers in the Semi-Arid Northeast, Brazil. *J. Range Manag. Arch.* 52, 241–248.

Albuquerque, S.G. de, Soares, J.G.G., Araujo Filho, J.A. de (1982): Densidade de Espécies Arbóreas e Arbustivas em Vegetação de Caatinga (No. 16). Embrapa-CPATSA, Petrolina.

Albuquerque, U.P. de, Araújo, E. de L., El-Deir, A.C.A., Lima, A.L.A. de, Souto, A., Bezerra, B.M., Ferraz, E.M.N., Freire, E.M.X., Barreto Sampaio, E.V. de S.B., Las-Casas, F.M.G., Moura, G.J.B. de, Pereira, G.A., Melo, J.G. de, Ramos, M.A., Rodal, M.J.N., Schiel, N., Lyra-Neves, R.M. de, Alves, R.R.N., Azevedo-Júnior, S.M. de, Telino Júnior, W.R., Severi, W. (2012): Caatinga Revisited: Ecology and Conservation of an Important Seasonal Dry Forest. *Sci. World J.* 2012, 1–18.

Albuquerque, U.P. de, Medeiros, P.M. de, Almeida, A.L.S. de, Monteiro, J.M., Neto, E.M. de F.L., Melo, J.G. de, Santos, J.P. dos (2007): Medicinal Plants of the Caatinga (Semi-Arid) Vegetation of NE Brazil: A Quantitative Approach. *J. Ethnopharmacol.* 114, 325–354.

Albuquerque, U.P. de, Oliveira, R.F. de (2007): Is the Use-Impact on Native Caatinga Species in Brazil Reduced by the High Species Richness of Medicinal Plants? *J. Ethnopharmacol.* 113, 156–170.

Albuquerque, U.P. de, Soldati, G.T., Sieber, S.S., Medeiros, P.M. de, Sá, J.C. de, Souza, L.C. de (2011): Rapid Ethnobotanical Diagnosis of the Fulni-Ô Indigenous Lands (NE Brazil): Floristic Survey and Local Conservation Priorities for Medicinal Plants. *Environ. Dev. Sustain.* 13, 277–292.

Almeida, A.L.S., Albuquerque, U.P. de, Castro, C.C. (2011): Reproductive Biology of *Spondias tuberosa* Arruda (Anacardiaceae), an Endemic Fructiferous Species of the Caatinga (Dry Forest), Under Different Management Conditions in Northeastern Brazil. *J. Arid Environ.* 75, 330–337.

Almeida, C. d. F.C.B. d. R., Ramos, M.A., Amorim, E.L.C. de, Albuquerque, U.P. de (2010): A Comparison of Knowledge About Medicinal Plants for Three Rural Communities in the Semi-Arid Region of Northeast of Brazil. *J. Ethnopharmacol.* 127, 674–684.

Almeida, W.R., Lopes, A.V., Tabarelli, M., Leal, I.R. (2014): The Alien Flora of Brazilian Caatinga: Deliberate Introductions Expand the Contingent of Potential Invaders. *Biol. Invasions* 17, 51–56.

Alves, J.N., de Araújo, G.G.L., Porto, E.R., da Cunha Castro, J.M., de Souza, L.C. (2007): Feno de Erva-Sal (*Atriplex nummularia* Lindl.) e Palma Forrageira (*Opuntia ficus* Mill.) em Dietas para Caprinos e Ovinos. *Rev. Científica Produção Anim.* 9.

Alves, R.R.N., Mendonça, L.E.T., Confessor, M.V.A., Vieira, W.L.S., Lopez, L.C.S. (2009): Hunting Strategies Used in the Semi-Arid Region of Northeastern Brazil. *J. Ethnobiol. Ethnomedicine* 5, 12.

Andrade, M.W. de, Mendonça, V., Hafle, O.M., de Medeiros, P.V.Q., Mendonça, L.F.M. (2013): Adubos Nitrogenados e Potássicos na Produção de Porta- Enxenrtos de Umbuzeiro (*Spondias tuberosa* Arr. Cam.). *Rev. Caatinga* 26, 117–122.

Aoudia, H., Oomah, B.D., Zaidi, F., Zaidi-Yahiaoui, R., Drover, J.C., Harrison, J.E. (2013): Phenolics, Antioxidant and Anti-Inflammatory Activities of *Melia azedarach* Extracts. *Int. J. Appl. Res. Nat. Prod.* 6, 19–29.

APAC (2015): Sistema de Informação Geográfica, Apac - Agência Pernambucana de Águas e Clima [WWW Document]. URL http://www.apac.pe.gov.br/sighpe/ (accessed 4.28.17).

Aragão, F.A.S. de, Souza, F.X. de, Torres, S.B. (2008): Otimização da Quebra de Dormência de Sementes de Umbu, in: Conference Proceedings Congressso Brasileiro de Fruticultura. Presented at the Congressso Brasileiro de Fruticultura, SBF, Vitoria, ES, p. 6.

Araújo, F.P. de, Neto, M.T. de C. (2002): Influência de Fatores Fisiológicos de Plantas-Matrizes e de Épocas do Ano no Pegamento de Diferentes Métodos de Enxertia do Umbuzeiro. *Rev. Bras. Frutic.* 24, 752–755.

Araújo, F.P. de, Santos, C.A.F., Cavalcanti, N. de B., Resende, G.M. de (2001): Influência do Período de Armazenamento das Sementes de Umbuzeiro na Sua Germinação e no Desenvolvimento da Plântula. *Rev. Bras. Armazenamento* 2, 36–39.

Araujo, E.L., Medeiros, M.K.M., Silva, V.E., Zucchi, R.A. (2005): Fruit Flies (Diptera: Tephritidae) in the Semi-Arid Region of the State of Rio Grande do Norte, Brazil: Host Plants and Infestation Indices. *Neotrop. Entomol.* 34, 889–894.

Araújo Filho, J.C. (2011): Relação Solos e Paisagem no Bioma Caatinga., in: Congress Proceedings Simpósio Brasileiro de Geografia Física Aplicada 14. Presented at the Simpósio Brasileiro de Geografia Física Aplicada 14, UFGD, Dourados, Dourados, MS, p. 23.

Araújo Filho, J.C., Gunkel, G., Sobral, M.C.M., Kaupenjohann, M., Lopes, H.L. (2013): Soil Attributes Functionality and Water Eutrophication in the Surrounding Area of Itaparica Reservoir, Brazil. *Rev. Bras. Eng. Agríc. E Ambient.* 17, 1005–1013.

Armstrong, W., Drew, M.C. (2002): Root Growth and Metabolism Under Oxygen Deficiency, in: Waisel, Y., Eshel, A., Kafkafi, U. (eds.): Plant Roots: The Hidden Half. Marcel Dekker, New York, Basel, pp. 729–761.

Arndt, S.K., Clifford, S.C., Wanek, W., Jones, H.G., Popp, M. (2001): Physiological and Morphological Adaptations of the Fruit Tree *Ziziphus rotundifolia* in Response to Progressive Drought Stress. *Tree Physiol.* 21, 705–715.

Arriaga, F.J., Lowery, B. (2003): Soil Physical Properties and Crop Productivity of an Eroded Soil Amended with Cattle Manure. *Soil Sci.* 168, 888–899.

Asghari, S., Neyshabouri, M.R., Abbasi, F., Aliasgharzad, N., Oustan, S. (2009): The Effects of Four Organic Soil Conditioners on Aggregate Stability, Pore Size Distribution, and Respiration Activity in a Sandy Loam Soil. *Turk. J. Agric. For.* 33, 47–55.

Atkinson, C.J., Fitzgerald, J.D., Hipps, N.A. (2010): Potential Mechanisms for Achieving Agricultural Benefits from Biochar Application to Temperate Soils: A Review. *Plant Soil* 337, 1–18.

Avocèvou-Ayisso, C., Sinsin, B., Adégbidi, A., Dossou, G., Van Damme, P. (2009): Sustainable Use of Non-Timber Forest Products: Impact of Fruit Harvesting on *Pentadesma butyracea* Regeneration and Financial Analysis of Its Products Trade in Benin. *For. Ecol. Manag.* 257, 1930–1938.

Azevedo, C.S. de, Silva, M.C. da, Teixeira, T.P., Young, R.J., Garcia, Q.S., Rodrigues, M. (2013): Effect of Passage Through the Gut of Greater Rheas on the Germination of Seeds of Plants of Cerrado and Caatinga Grasslands. *Emu* 113, 177–182.

Bagarello, V., Di Prima, S., Iovino, M., Provenzano, G. (2014): Estimating Field-Saturated Soil Hydraulic Conductivity by a Simplified Beerkan Infiltration Experiment. *Hydrol. Process.* 28, 1095–1103.

Bakker, J.D., Colasurdo, L.B., Evans, J.R. (2012): Enhancing Garry Oak Seedling Performance in a Semiarid Environment. *Northwest Sci.* 86, 300–309.

Barber, S.A. (1962): A Diffusion and Mass-Flow Concept of Soil Nutrient Availability. *Soil Sci.* 93, 39–49.

Bärnighausen, T., Bloom, D.E., Cafiero, E.T., O'Brien, J.C. (2013): Valuing the Broader Benefits of Dengue Vaccination, with a Preliminary Application to Brazil. *Semin. Immunol.* 25, 104–113.

Barreto, L.S., Castro, M.S. de (2007): Conservação do Umbuzeiro (*Spondias tuberosa* Arr. Câmara) e de seus Polinizadores no Contexto Agroecológico Para a Agricultura Familiar Indígena Pankararé no Semi-Árido. *Rev. Bras. Agroecol.* 2, 1580–1583.

Barreto, L.S., Castro, M.S. d. (2010): Boas Práticas de Manejo para o Extrativismo Sustentável do Umbu. Embrapa Recursos Genéticos e Biotecnologia, Brasília.

Barreto, L.S., Leal, S.M., Anjos, J.C. dos, Castro, M.S. de (2006): Tipos Polínicos dos Visitantets Floraus do Umbuzeiro (*Spondias tuberosa*, Anacardiaceae), no Territóio Indígena Pankararé, Raso da Catarina, Bahia, Brasil. *Candombá - Rev. Virtual* 2, 80–85.

Bartaburu, X. (2013): Umbu, Fruta da Resistência [WWW Document]. URL http://www.achaaquibrasil.com.br/blog/umbu-fruta-da-resistencia.html (accessed 4.28.17).

Basso, A.S., Miguez, F.E., Laird, D.A., Horton, R., Westgate, M. (2013): Assessing Potential of Biochar for Increasing Water-Holding Capacity of Sandy Soils. *GCB Bioenergy* 5, 132–143.

Bauer, A. (1974): Influence of Soil Organic Matter on Bulk Density and Available Water Capacity of Soils. *Farm Res.* 31, 44–52.

Beuchle, R., Grecchi, R.C., Shimabukuro, Y.E., Seliger, R., Eva, H.D., Sano, E., Achard, F. (2015): Land Cover Changes in the Brazilian Cerrado and Caatinga Biomes from 1990 to 2010 Based on a Systematic Remote Sensing Sampling Approach. *Appl. Geogr.* 58, 116–127.

Beusch, C., Kaupenjohann, M. (2015): Addition of Biochar and Clay Increase the Nutrient Retention of a Tropical Arenosol, in: Management of Land Use Systems for Enhanced Food Security – Conflicts, Controversies and Resolutions. Book of Abstracts. Presented at the Tropentag, Cuvillier Verlag, Göttingen, Berlin.

Bhuyan, P., Khan, M.L., Tripathi, R.S. (2003): Tree Diversity and Population Structure in Undisturbed and Human-Impacted Stands of Tropical Wet Evergreen Forest in Arunachal Pradesh, Eastern Himalayas, India. *Biodivers. Conserv.* 12, 1753–1773.

Bird, A. (2007): Perceptions of Epigenetics. *Nature* 447, 396–398.

Bitterwolf, S. (2014): Population Structure and Allometric Assessment of Umbuzeiro (*Spondias tuberosa* Arruda) in Pernambuco, Brazil. Bachelor Thesis, Universität Hohenheim, Stuttgart.

Blain, D., Kellman, M. (1991): The Effect of Water Supply on Tree Seed Germination and Seedling Survival in a Tropical Seasonal Forest in Veracruz, Mexico. *J. Trop. Ecol.* 7, 69–83.

Bloom, A.J., Chapin, F.S., Mooney, H.A. (1985): Resource Limitation in Plants-An Economic Analogy. *Annu. Rev. Ecol. Syst.* 16, 363–392.

Böhm, W. (1979): Methods of Studying Root Systems. Springer Berlin Heidelberg, Berlin, Heidelberg.

Borges, S.V., Maia, M.C.A., Gomes, R. d. C.M., Cavalcanti, N.B. (2007): Chemical Composition of Umbu (*Spondias tuberosa* Arr. Cam) Seeds. *Quím. Nova* 30, 49–52.

Brunner, I., Herzog, C., Dawes, M.A., Arend, M., Sperisen, C. (2015): How Tree Roots Respond to Drought. *Front. Plant Sci.* 6.

Caetano, S., Prado, D., Pennington, R.T., Beck, S., Oliveira-Filho, A., Spichiger, R., Naciri, Y. (2008): The history of Seasonally Dry Tropical Forests in Eastern South America: Inferences from the Genetic Structure of the Tree *Astronium urundeuva* (Anacardiaceae). *Mol. Ecol.* 17, 3147–3159.

Campello, F.B., Gariglio, M.A., da Silva, J.A., de Araújo Leal, A.M. (1999): Diagnóstico Florestal da Região Nordeste. IBAMA, Brasília.

Castelletti, C.H.M., Santos, A.M.M., Tabarelli, M., Silva, J.M.C. da (2003): Quanto Ainda Resta da Caatinga? Uma Estimativa Prelininar, in: Tabarelli, M., Leal, I.R., Silva, J.M.C. (eds.): Ecologia E Conservação Da Caatinga. Editora Universitária, Universidade Federal de Pernambuco, Recife, pp. 719–734.

Cavalcanti, A.C. (1999): Diagnóstico Ambiental do Município de Petrolina. *Pernamb. Embrapa–CNPS ERPNE.*

Cavalcanti, N. de B. (2007): Fatos e Fotos da Caatinga: A Regeneração Natural e Dispersão de Sementes de Imbuzeiro na Caatinga [WWW Document]. URL http://fatosefotosdacaatinga.blogspot.com.br/2007/04/regenerao-natural-e-disperso-de.html (accessed 4.28.17).

Cavalcanti, N. de B. (2008): Aspectos do Crescimento, Desenvolvimento e Manejo Cultural do Imbuzeiro., in: Lederman, I.E., Lira Júnior, J.S. de, Silva Júnior, J.F. da (eds.): Spondias no Brasil: Umbu, Cajá e Espécies Afins. IPA; Embrapa Agroindústria Tropical; UFRPE, Recife, pp. 127–134.

Cavalcanti, N. de B. (2013): Regeneração Natural e Dispersão de Sementes do Imbuzeiro (*Spondias tuberosa* Arruda) no Sertão de Pernambuco [WWW Document]. URL http://imbuzeiro.blogspot.com.br/ (accessed 4.28.17).

Cavalcanti, N. de B., Drumond, M.A., Resende, G.M. de (2004a): Uso das Folhas do Umbuzeiro (*Spondias tuberosa* Arruda) na Alimentação de Caprinos e Ovinos no Semi-Árido Nordestino. *Agrossilvicultura* 1, 131–134.

Cavalcanti, N. de B., Resende, G.M. de (2003): Consumo de Frutos e Predação de Sementes do Imbuzeiro (*Spondias tuberosa* Arruda) Pelo Cancão (*Cyanocorax cyanopogon*)., in: Conference Proceedings Congresso Nacional de Botânica 54. Presented at the Congresso Nacional de Botânica, Museu Paraense Emílio Goeldi; Embrapa Amzônia Oriental, Belém, PA, p. 1.

Cavalcanti, N. de B., Resende, G.M. de (2005): Riscos de Extinçãodo Imbuzeiro (*Spondias tuberosa* Arruda) no Semi-Árido do Nordeste [WWW Document]. URL http://www.imbubrasil.jex.com.br/artigos/riscos+de+extincao+do+imbuzeiro+spondias+tuberosa+arruda+no+semi-arido+do+nordeste (accessed 4.28.17).

Cavalcanti, N. de B., Resende, G.M. de (2006): Ocorrência de Xilopodio em Plantas nativas de Imbuzeiro. *Rev. Caatinga* 19, 287–293.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2000): Ciclo Reprodutivo do Imbuzeiro (*Spondias tuberosa*, Arr. Cam.) no Semi-Arido do Nordeste Brasileiro. *Rev. Ceres* 47, 421–439.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2002a): Emergência e Crescimento do Imbuzeiro (*Spondias tuberosa* Arr. Cam.) em Diferentes Substratos. *Rev. Ceres* 49, 97–108.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2002b): Levantamento da Produção de Xilopódio e os Efeitos de sua Retirada Sobre a Frutificação e Persistência de Plantas Nativas de Imbuzeiro (*Spondias tuberosa* Arr. Cam.). *Ciênc. E Agrotecnologia* 26, 927–942.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2006a): Emergência e Sobrevivência de Plântulas de Imbuzeiro (*Spondias tuberosa* Arruda) na Caatinga. *Rev. Caatinga* 19, 391–396.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2008a): Problemas Encontrados na Regeneração Natural do Imbuzeiro (*Spondias tuberosa* Arruda) no Sertão de Pernambuco., in: Conference proceedings Simpósio Brasileiro sobre Umbu, Cajá e Espécies afins. Presented at the Simpósio Brasileiro sobre Umbu, Cajá e Espécies afins, Embrapa Semiárido, Recife, PE, p. 5.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2009a): Regeneração Natural e Dispersão de Sementes do Imbuzeiro (*Spondias tuberosa* Arruda) no Sertão de Pernambuco. *Eng. Ambient.* 6, 342–357.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2009b): Danos Causados a Plantas Jovens de Imbuzeiro (*Spondias tuberosa* Arruda) em Área de Caatinga Nativa e Degradada por Animais. *Eng. Ambient.* 6, 91–102.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2010): O Crescimento de Plantas de Imbuzeiro (*Spondias tuberosa* Arruda) no Semiárido de Pernambuco. *Eng. Ambient.* 7, 21–31.

Cavalcanti, N. de B., Resende, G.M. de, Brito, L.T. de L. (2011): Irrigação Suplementar do Imbuzeiro (*Spondias tuberosa* Arruda). *Eng. Ambient.* 8, 252–264.

Cavalcanti, N. de B., Resende, G.M. de, Drumond, M.A. (2006b): Período de Dormência de Sementes de Imbuzeiro. *Rev. Caatinga* 19, 135–139.

Cavalcanti, N. de B., Resende, G.M. (2004): Danos Provocados Por Insetos a Sementes do Imbuzeiro no Semi-Árido do Nordeste Brasileiro. *Caatinga* 17, 93–97.

Cavalcanti, N. de B., Resende, G.M., Brito, L.T. de L. (2008b): Densidade e Produtividade de Plantas Nativas de Umbuzeiro (*Spondias tuberosa*, Arruda) na Caatinga da Bahia ePernambuco., in: Conference proceedings Simpósio Brasileiro sobre Umbu, Cajá e Espécies afins. Presented at the Simpósio Brasileiro sobre Umbu, Cajá e Espécies afins, IPA; Embrapa Agroindústria Tropical; UFRPE, Recife, PE, p. 5.

Cavalcanti, N. de B., Santos, C.A.F., Resende, G.M. de, Brito, L.T. de L., Anjos, J.B. dos (2004b): Picles do Xilopódio do Umbuzeiro (*Spondias tuberosa* Arruda). (No. 64). Embrapa Semi-Árido, Petrolina.

Chapin, F.S., III (1980): The Mineral Nutrition of Wild Plants. *Annu. Rev. Ecol. Syst.* 11, 233–260.

Chapin, F.S., III, Schulze, E.-D., Mooney, H.A. (1990): The Ecology and Economics of Storage in Plants. *Annu. Rev. Ecol. Syst.* 21, 423–447.

Cheng, Y., Han, Y., Wang, Q., Wang, Z. (2006): Seasonal Dynamics of Fine Root Biomass, Root Length Density, Specific Root Length, and Soil Resource Availability in a *Larix gmelinii* Plantation. *Front. Biol. China* 1, 310–317.

Climate-Data.org (2016): Climate: Petrolândia [WWW Document]. URL http://de.climate-data.org/location/880329/ (accessed 4.28.17).

Cook, F.J., Knight, J.H., Kelliher, F.M. (2013): Modelling Oxygen Transport in Soil with Plant Root and Microbial Oxygen Consumption: Depth of Oxygen Penetration. *Soil Res.* 51, 539–553.

Costa, R.C. da, Araújo, F.S. de, Lima-Verde, L.W. (2007): Flora and Life-Form Spectrum in an Area of Deciduous Thorn Woodland (Caatinga) in Northeastern, Brazil. *J. Arid Environ.* 68, 237–247.

Costa, T.C. e C. da, Oliveira, M.A.J. de, Accioly, L.J. de O., Silva, F.H.B.B. da (2009): Analysis of Degradation of “Caatinga” in the Desertification Nucleus of Seridó - Brazil. *Rev. Bras. Eng. Agríc. E Ambient.* 13, 961–974.

Côté, S.D., Rooney, T.P., Tremblay, J.-P., Dussault, C., Waller, D.M. (2004): Ecological Impacts of Deer Overabundance. *Annu. Rev. Ecol. Evol. Syst.* 35, 113–147.

Crawford, R.M.M. (1992): Oxygen Availability as an Ecological Limit to Plant Distribution, in: Fitter, M.B. and A.H. (ed.): Advances in Ecological Research. Academic Press, pp. 93–185.

Cunha, A.P.M., Alvalá, R.C., Nobre, C.A., Carvalho, M.A. (2015): Monitoring Vegetative Drought Dynamics in the Brazilian Semiarid Region. *Agric. For. Meteorol.* 214–215, 494–505.

Cunha, L.H., Gomes, R.A. (2012): A Trajetória da Algaroba no Semiárido Nordestino: Dilemas Políticos e Científicos. *Raízes* 32, 72–95.

Dekker, L.W., Ritsema, C.J., Oostindie, K., Moore, D., Wesseling, J.G. (2009): Methods for Determining Soil Water Repellency on Field-Moist Samples: Measuring Water Repellency on Field-Moist Samples. *Water Resour. Res.* 45, n/a-n/a.

Dempster, D.N., Jones, D.L., Murphy, D.V. (2012): Clay and Biochar Amendments Decreased Inorganic but Not Dissolved Organic Nitrogen Leaching in Soil. *Soil Res.* 50, 216–221.

DIN / ISO 10390: Soil quality - Determination of pH (2005): . International Organization for Standardization, Geneva, Switzerland.

DIN / ISO 11277: Soil quality - Determination of particle size distribution in mineral soil material - Method by sieving and sedimentation (2002): . International Organization for Standardization, Geneva, Switzerland.

Dirzo, R., Young, H.S., Mooney, H.A., Cabellos, G. (2011): Introduction, in: Dirzo, R., Young, H.S., Mooney, H.A., Cabellos, G. (eds.): Seasonally Dry Tropical Forests: Ecology and Conservation. Island Press, Washington, pp. xi–xiii.

Djajadi, Abbott, L.K., Hinz, C. (2012): Synergistic Impacts of Clay and Organic Matter on Structural and Biological Properties of a Sandy Soil. *Geoderma* 183–184, 19–24.

Dobos, E. (2011): Albedo, in: Lal, R. (ed.): Encyclopedia of Soil Science. Taylor & Francis, New York, NY, pp. 64–66.

Donagema, G.K., Campos, D.V.B. de, Calderano, S.B., Teixeira, W.G., Viana, J.H.M. (Eds.) (2011): Manual de Métodos de Análise de Solo, 2nd ed. Embrapa Solos, Rio de Janeiro.

Drumond, M.A., Kiill, L.H.P., Lima, P.C.F., Oliveira, M.C. de, Oliveira, V.R. de, Albuquerqe, S.G. de, Nascimento, C.E.S., Cavalcante, J. (2004): Estratégias para o Uso Sustentável da Biodiversidade da Caatinga, in: Silva, J.M.C., Tabarelli, M., Fonseca, M.T. da, Lins, L.V. (eds.): Biodiversidade Da Caatinga: Áreas E Ações Prioritárias Para a Conservação. Ministério do Meio Ambiente, Brasília, pp. 329–340.

Drumond, M.A., Lima, P.C.F., Souza, S.M. de, Lima, J.L.S. de (1982): Sociabilidade das Espécies Florestais da Caatinga em Santa Maria da Boa Vista,PE. *Bol. Pesqui. Florest.* 4, 47–59.

Drumond, M.A., Nascimento, C.E.S., Morgado, L.B. (2001): Desenvolvimento Inicial do Umbuzeiro *Spondias tuberosa* Arruda) no Semi-Árido Pernambucano., in: Conference Proceedings Simpósio Brasiliero de Captacao de Agua de Chuva No Semi-Arido 3. Presented at the Simposio Brasiliero de Captacao de Agua de Chuva no Semi-Arido, Embrapa Algodao; Embrapa Semi-Arido, Campina Grande, PB, p. 6.

Duque, J.G. (2004): O Nordeste e as Lavouras Xerófilas, 4th ed. Banco do Nordeste do Brasil, Fortaleza.

Dutra, T.R., Massad, M.D., Sarmento, M.F.Q., Oliveira, J.C. de (2012): Ácido Indolbutírico e Substratos na Alporquia de Umbuzeiro. *Pesqui. Agropecuária Trop.* 42, 424–429.

ECOD (2013): Lista Mostra 24 Alimentos Brasileiros em Risco de Extinção [WWW Document]. URL http://www.ecodesenvolvimento.org/posts/2013/junho/lista-mostra-24-alimentos-brasileiros-em-risco-de?tag=biodiversidade (accessed 4.28.17).

Elrick, D.E., Reynolds, W.D. (1992): Methods for Analyzing Constant-Head Well Permeameter Data. *Soil Sci. Soc. Am. J.* 56, 320–323.

Embrapa (1991): Programa Nacional de Pesquisa em Fruteiras de Clima Tropical-PNPFCT. EMBRAPA/CNPMF, Cruz das Almas.

Epstein, L. (1998): A Riqueza do Umbuzeiro. *Rev. Bahia Agríc.* 2, 31–34.

Espindola, A., Almeida, C., Carvalho, N., Roza, M. (2004): Diâmetro do Caula e Métoda de Enxertia na Formação de Mudas de Umbuzeiro (*Spondias tuberosa* Arr. Cam.). *Curr. Agric. Sci. Technol.* 10.

Evans, J.D. (1996): Straightforward Statistics for the Behavioral Sciences. Brooks/Cole Pub. Co, Pacific Grove.

Fabricante, J.R. (Ed.) (2013): Plantas Exóticas e Exóticas Invasoras da Caatinga. Bookess, Florianópolis, SC.

Ferreira, J.V.A. (2014): Influência de Fatores Bióticos e Abióticos Para a Conservação de *Spondias tuberosa* Arruda, Anacardiaceae nas Caatingas. Bachelor Thesis, Universidade Federal do Vale do São Francisco, Petrolina.

Ferri, M.G. (1953): Water Balance of Plants from Caatinga II. Further Information on Transpiration and Stomata Behavior. *Rev. Bras. Biol.* 3, 237–244.

Ferri, M.G., Labouriau, L.G. (1952): Water Balance of Plants from Caatinga I. Transpiration of Some of the Most Frequent Species of the Caatinga of Paulo Afonso (Bahia) in the Rainy Season. *Rev. Bras. Biol.* 3, 301–312.

Franca-Rocha, W., Nolasco, M.C., Lobão, J., Britto, D., Chaves, J.M. (2007): Levantamento da Cobertura Vegetal e do Uso do Solo do Bioma Caatinga, in: Conference Proceedings XIII Simpósio Brasileiro de Sensoriamento Remoto. Presented at the Simpósio Brasileiro de Sensoriamento Remoto, INPE, Florianópolis, SC, pp. 2629–2636.

Frankham, R. (2005): Genetics and Extinction. *Biol. Conserv.* 126, 131–140.

Fraser, E.D.G., Dougill, A.J., Hubacek, K., Quinn, C.H., Sendzimir, J., Termansen, M. (2011): Assessing Vulnerability to Climate Change in Dryland Livelihood Systems: Conceptual Challenges and Interdisciplinary Solutions. *Ecol. Soc.* 16.

Freire, F.C.O., Bezerra, J.L. (2001): Foliar Endophytic Fungi of Ceará State (Brazil): A Preliminary Study. *Summa Phytopathol.* 27, 304–308.

Galvez, D.A., Landhäusser, S.M., Tyree, M.T. (2013): Low Root Reserve Accumulation During Drought May Lead to Winter Mortality in Poplar Seedlings. *New Phytol.* 198, 139–148.

Gerhardt, K., Hytteborn, H. (1992): Natural Dynamics and Regeneration Methods in Tropical Dry Forests: An Introduction. *J. Veg. Sci.* 3, 361–364.

Gill, R.M.A. (1992): A Review of Damage by Mammals in North Temperate Forests: 3. Impact on Trees and Forests. *Forestry* 65, 363–388.

GIMP Developers (1995): GIMP: GNU Image Manipulation Program.

Giongo, V., GalVÃo, S. da S., Mendes, A.M.S., Gava, C.A.T., Cunha, T.J.F. (2011): Soil Organic Carbon in the Brazilian Semi-Arid Tropics. *Dyn. Soil Dyn. Plant* 5, 12–20.

Giulietti, A.M., Bocage Neta, A.L., Castro, A., Gamarra-Rojas, C.F.L., Sampaio, E., Virgínio, J.F., Queiroz, L.P., Figueiredo, M.A., Rodal, M.J.N., Barbosa, M.R.V. (2004): Diagnóstico da Vegetação Nativa do Bioma Caatinga, in: Silva, J.M.C., Tabarelli, M., Fonseca, M.T. da, Lins, L.V. (eds.): Biodiversidade Da Caatinga: Áreas E Ações Prioritárias Para a Conservação. Ministério do Meio Ambiente, Brasília, pp. 48–90.

Gomes, G.M. (2001): Velhas Secas em Novos Sertões: Continuidade e Mudanças na Economia do Semi-Árido e dos Cerrados Nordestinos. IPEA, Brasília.

Gomes, W.A., Mendonça, R.M.N., de Souza, E.P., Estrela, M.A., Melo, V.S., Silva, S.M., de Souza, A.P. (2010): Garfagem e Diâmetro de Porta-Enxerto na Obtenção de Mudas de Umbuzeiro do Acesso Laranja. *Rev. Bras. Frutic.* 32, 952–959.

Gonçalves Júnior, O. (2011): Entre Bois e Cabras: Uma Visão Histórica Sobre Mentalidades e Valores nos Sertões. *Rev. Estud. Históricos* 24, 49–68.

Gray, M., Johnson, M.G., Dragila, M.I., Kleber, M. (2014): Water Uptake in Biochars: The Roles of Porosity and Hydrophobicity. *Biomass Bioenergy* 61, 196–205.

Grieser, J. (2005): New_LocClim. FAO, Rome.

Griz, L.M.S., Machado, I.C.S. (2001): Fruiting Phenology and Seed Dispersal Syndromes in Caatinga, a Tropical Dry Forest in the Northeast of Brazil. *J. Trop. Ecol.* 17, 303–321.

Guariguata, M.R., Pinard, M.A. (1998): Ecological Knowledge of Regeneration from Seed in Neotropical Forest Trees: Implications for Natural Forest Management. *For. Ecol. Manag.* 112, 87–99.

Guevara, A., Giordano, C.V., Aranibar, J., Quiroga, M., Villagra, P.E. (2010): Phenotypic Plasticity of the Coarse Root System of *Prosopis flexuosa*, a Phreatophyte Tree, in the Monte Desert (Argentina). *Plant Soil* 330, 447–464.

Gutiérrez-Granados, G., Juárez, V., Alcalá, R.E. (2011): Natural and Human Disturbances Affect Natural Regeneration of *Swietenia macrophylla*: Implications for Rainforest Management. *For. Ecol. Manag.* 262, 161–169.

Hagel, H., Hoffmann, C., Ferreira Irmao, J., Doluschitz, R. (2014): Socio-Economic Analysis of Irrigated Family Farming in Brazil's Semi-Arid Northeast. *Submitt. J. Rural Stud.*

Halvorson, A.D. (2006): Nutrient-Water Interactions, in: Lal, R. (ed.): Encyclopedia of Soil Science. Taylor & Francis, New York, pp. 1161–1163.

Hambler, C., Canney, S.M. (2013): Conservation, 2nd ed. ed. Cambridge University Press, Cambridge, United Kingdom/New York, NY, USA.

Hardie, M., Clothier, B., Bound, S., Oliver, G., Close, D. (2014): Does Biochar Influence Soil Physical Properties and Soil Water Availability? *Plant Soil* 376, 347–361.

Harmer, R. (2001): The Effect of Plant Competition and Simulated Summer Browsing by Deer on Tree Regeneration. *J. Appl. Ecol.* 38, 1094–1103.

Harrington, T.B., Bluhm, A.A. (2001): Tree Regeneration Responses to Microsite Characteristics Following a Severe Tornado in the Georgia Piedmont, USA. *For. Ecol. Manag.* 140, 265–275.

Haynes, R.J., Naidu, R. (1998): Influence of Lime, Fertilizer and Manure Applications on Soil Organic Matter Content and Soil Physical Conditions: A Review. *Nutr. Cycl. Agroecosystems* 51, 123–137.

He, Z., Fu, M., Mao, L. (2011): Total Phenolic, Condensed Tannin and Antioxidant Activity of Four *Carya* Species from China. *Afr. J. Biotechnol.* 10, 10472–10477.

Hoffmann, C., Jungk, A. (1995): Growth and Phosphorus Supply of Sugar Beet as Affected by Soil Compaction and Water Tension. *Plant Soil* 176, 15–25.

Hoffmann, M., Brooks, T.M., Fonseca, G.A.B. da, Gascon, C., Hawkins, A.F.A., James, R.E., Langhammer, P., Mittermeier, R.A., Pilgrim, J.D., Rodrigues, A.S.L., Silva, J.M.C. (2008): Conservation Planning and the IUCN Red List. *Endanger. Species Res.* 6, 113–125.

Holdridge, L.R. (1947): Determination of World Plant Formations from Simple Climatic Data. *Science* 105, 367–368.

Holdridge, L.R. (1967): Life Zone Ecology. Tropical Science Center, San Jose, Costa Rica.

Holdridge, L.R., Grenke, W.C., Hatheway, W.C., Liang, T., Tosi, Jr., J.A. (1971): Forest Environments in Tropical Life Zones: A Pilot Study. Pergermon Press, Oxford.

Hudson, N. (1987): Soil and Water Conservation in Semi-arid Areas. Food and Agriculture Organization of the United Nations, Rome.

IBGE (2004): Mapa de Biomas e de Vegetação [WWW Document]. URL http://www.ibge.gov.br/home/presidencia/noticias/21052004biomashtml.shtm (accessed 4.28.17).

IBGE (2005): Mapa do Semiárido Brasileiro.

IBGE (2009): Censo Agropecuário 2006 [WWW Document]. URL http://www.ibge.gov.br/home/estatistica/economia/agropecuaria/censoagro/default.shtm (accessed 4.28.17).

IBGE (2013): Produção da Extração Vegetal e da Silvicultura 2012 [WWW Document]. URL http://www.ibge.gov.br/home/estatistica/economia/pevs/2012/default_ods_mesor_mic_mun.shtm (accessed 4.28.17).

IBGE (2015): Produção da Pecuária Municipal 2014 [WWW Document]. URL http://www.ibge.gov.br/home/estatistica/economia/ppm/2014/default_ods.shtm (accessed 4.28.17).

IBGE (2016): IBGE-Cidades@ [WWW Document]. URL http://cidades.ibge.gov.br/xtras/perfil.php?lang=&codmun=2611002 (accessed 4.28.17).

IPCC (2007a): Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom/New York, NY, USA.

IPCC (2007b): Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

IRPAA (n.d.): Recaatingamento, IRPAA - Instituto Regional da Pequena Agropecuária Apropriada [WWW Document]. URL http://www.irpaa.org/modulo/recaatingamento (accessed 4.28.17).

Ismail, S.M., Ozawa, K. (2007): Improvement of Crop Yield, Soil Moisture Distribution and Water Use Efficiency in Sandy Soils by Clay Application. *Appl. Clay Sci.* 37, 81–89.

IUCN (2012): IUCN Red List Categories and Criteria, Version 3.1. Second edition. ed. IUCN, Gland, Switzerland and Cambridge, UK.

IUCN (2016): The IUCN Red List of Threatened Species. Version 2016-3 [WWW Document]. URL http://www.iucnredlist.org (accessed 4.28.17).

IUSS Working Group WRB (2014): World Reference Base for Soil Resources 2014, Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. FAO, Rome.

Ivanov, D.S., Lević, J.D., Sredanović, S.A. (2010): Fatty Acid Composition of Various Soybean Products. *Food Feed Res.* 2, 65–70.

Jbir, N., Chaïbi, W., Ammar, S., Jemmali, A., Ayadi, A. (2001): Root Growth and Lignification of Two Wheat Species Differing in their Sensitivity to NaCl, in Response to Salt Stress. *Comptes Rendus Académie Sci. - Ser. III - Sci. Vie* 324, 863–868.

Jeffery, S., Meinders, M.B.J., Stoof, C.R., Bezemer, T.M., van de Voorde, T.F.J., Mommer, L., van Groenigen, J.W. (2015): Biochar Application Does Not Improve the Soil Hydrological Function of a Sandy Soil. *Geoderma* 251–252, 47–54.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C. (2011): A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using Meta-Analysis. *Agric. Ecosyst. Environ.* 144, 175–187.

Jones, D.L., Rousk, J., Edwards-Jones, G., DeLuca, T.H., Murphy, D.V. (2012): Biochar-Mediated Changes in Soil Quality and Plant Growth in a Three Year Field Trial. *Soil Biol. Biochem.* 45, 113–124.

Júnior, W.S.F., Ladio, A.H., Albuquerque, U.P. de (2011): Resilience and Adaptation in the Use of Medicinal Plants with Suspected Anti-Inflammatory Activity in the Brazilian Northeast. *J. Ethnopharmacol.* 138, 238–252.

Jurisch, K., Hahn, K., Wittig, R., Bernhardt-Römermann, M. (2013): Land-Use Impact on the Growth and Survival of Seedlings and Saplings in West African Savannas. *J. Veg. Sci.* 24, 101–112.

Katyal, J.C., Vlek, P.L. (2000): Desertification: Concept, Causes and Amelioration. *ZEF-Discuss. Pap. Dev. Policy-Cent. Dev. Res. Univ Bonn Ger.* 65.

Keller, L.F., Waller, D.M. (2002): Inbreeding Effects in Wild Populations. *Trends Ecol. Evol.* 17, 230–241.

Khaleel, R., Reddy, K.R., Overcash, M.R. (1981): Changes in Soil Physical Properties Due to Organic Waste Applications: A Review. *J. Environ. Qual.* 10, 133–141.

Khurana, E., Singh, J. s. (2001): Ecology of Seed and Seedling Growth for Conservation and Restoration of Tropical Dry Forest: A Review. *Environ. Conserv.* 39–52.

Kinney, T.J., Masiello, C.A., Dugan, B., Hockaday, W.C., Dean, M.R., Zygourakis, K., Barnes, R.T. (2012): Hydrologic Properties of Biochars Produced at Different Temperatures. *Biomass Bioenergy* 41, 34–43.

Kitajima, K., Fenner, M. (2000): Ecology of Seedling Regeneration., in: Fenner, M. (ed.): Seeds: The Ecology of Regeneration in Plant Communities. CABI, Wallingford, pp. 331–359.

Kjeldahl, J. (1883): Neue Methode zur Bestimmung des Stickstoffs in organischen Körpern. *Z. Für Anal. Chem.* 22, 366–382.

Kochsiek, A., Tan, S., Russo, S.E. (2013): Fine Root Dynamics in Relation to Nutrients in Oligotrophic Bornean Rain Forest Soils. *Plant Ecol.* 214, 869–882.

Köppen, W. (1900): Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. *Geogr. Z.* 6, 593–611.

Köppen, W. (1936): Das geographische System der Klimate, in: Köppen, W., Geiger, R. (eds.): Handbuch Der Klimatologie. Gebrüder Borntraeger, Berlin, p. 44.

Lacerda, J.S. de, Pereira, W.E., Dias, T.J., Oliveira Freira, J.L. de, Neto, J.F.B., Souza Costa, D. de, Oliveira, C.J. de (2009): Avaliaçãodo Crescimento de Porta-Enxertos de Umbuzeiro (*Spondias tuberosa*) em Substratos Adubados com Nitrogênio e Boro. *Eng. Ambient.* 6, 519–531.

Landini, G. (2008): Advanced Shape Analysis with ImageJ, in: Proceedings of the Second ImageJ User and Developer Conference. Presented at the ImageJ User and Developer Conference, Luxembourg, pp. 116–121.

Leal, I.R., Da Silva, J.M.C., Tabarelli, M., Lacher, T.E. (2005): Changing the Course of Biodiversity Conservation in the Caatinga of Northeastern Brazil. *Conserv. Biol.* 19, 701–706.

Leal, I.R., Vicente, M., Tabarelli, M. (2003): Herbivoria por Caprinos na Caatinga da Região de Xingó: Uma Análise Preliminar, in: Leal, I.R., Tabarelli, M., Silva, J.M.C. (eds.): Ecologia E Conservação Da Caatinga. Editora Universitária, Universidade Federal de Pernambuco, Recife, pp. 695–715.

Leifeld, J., Fenner, S., Müller, M. (2007): Mobility of Black Carbon in Drained Peatland Soils. *Biogeosciences* 4, 425–432.

Leite, A.V. de L., Machado, I.C.S. (2010): Reproductive Biology of Woody Species in Caatinga, a Dry Forest of Northeastern Brazil. *J. Arid Environ.* 74, 1374–1380.

Lima, J.L.S. de (1996): Plantas Forrageiras das Caatingas Usos e Potencialidades. EMBRAPA-CPATSA/PNE/RBG-KEW, Petrolina.

Lima Filho, J.M.P. (2001): Internal Water Relations of the Umbu Tree Under Semi-Arid Conditions. *Rev. Bras. Frutic.* 23, 518–521.

Lima Filho, J.M.P. (2004): Gas Exchange of the Umbu Tree Under Semi-Arid Conditions. *Rev. Bras. Frutic.* 26, 206–208.

Lima Filho, J.M.P. (2007): Water Status and Gas Exchange of Umbu Plants (*Spondias tuberosa* Arr. Cam.) Propagated by Seeds and Stem Cuttings. *Rev. Bras. Frutic.* 29, 355–358.

Lima Filho, J.M.P., Silva, C.M.M. de S. (1988): Aspectos Fisiológicos do Umbuzeiro. *Pesqui. Agropecuária Bras.* 23, 1091–1094.

Lima, L.H. de C., Barbosa, F.M., Lacerda, A.V. de, Nunes, T.J. de O. (2015): Estudo da Variabilidade Sazonal da Precipitação e da Sobrevivência de Mudas do Umbuzeiro (*Spondias tuberosa* Arruda Cam.) Enxertadas em uma Área de Enriquecimento de Caatinga no Semiárido Paraibano., in: Seabra, G. (ed.): TERRA - Saúde Ambiental e Soberania Alimentar. Barlavento, Ituiutaba, pp. 1269–1276.

Lopes, H.L. (2012a): Itaparica Reservoir [WWW Document]. *Innov. Proj.* URL http://www.innovate.tu-berlin.de/fileadmin/fg123_innovate/images/gebiet/Helio_bearbeitet.jpg (accessed 4.28.17).

Lopes, H.L. (2012b): Innovate Project Study Region [WWW Document]. *Innov. Proj.* URL http://www.innovate.tu-berlin.de/fileadmin/fg123_innovate/images/gebiet/hl_itaparica-18x15__2012-07-03.jpg (accessed 4.28.17).

Lopes, P.S.N., Magalhães, H.M., Gomes, J.G., Júnior, B., Silva, D. da, Araújo, V.D. de (2009): Superação da Dormência de Sementes de Umbuzeiro (*Spondias tuberosa*, Arr. Câm.) Utilizando Diferentes Métodos. *Rev. Bras. Frutic.* 31, 872–880.

Luxmoore, R.J. (1981): Micro-, Meso-, and Macroporosity of Soil. *Soil Sci. Soc. Am. J.* 45, 671–672.

Lykke, A.M. (1998): Assessment of Species Composition Change in Savanna Vegetation by Means of Woody Plants' Size Class Distributions and Local Information. *Biodivers. Conserv.* 7, 1261–1275.

Machado, I.C.S., Barros, L.M., Sampaio, E.V.S.B. (1997): Phenology of Caatinga Species at Serra Talhada, PE, Northeastern Brazil. *Biotropica* 29, 57–68.

Magalhães, H.M., Gomes, J.G., Lopes, P.S.N., Júnior, D. da S.B., Fernandes, R.C. (2007): Superação da Dormência em Sementes de Umbuzeiro (*Spondias tuberosa* , Arr. Câmara) Submetidas a Diferentes Épocas de Armazenamento. *Rev. Bras. Agroecol.* 2, 1336–1339.

Malcolm, J.R., Markham, A., Neilson, R.P., Garaci, M. (2002): Estimated Migration Rates Under Scenarios of Global Climate Change. *J. Biogeogr.* 29, 835–849.

Marinho, F.P., Mazzochini, G.G., Manhães, A.P., Weisser, W.W., Ganade, G. (2016): Effects of Past and Present Land Use on Vegetation Cover and Regeneration in a Tropical Dryland Forest. *J. Arid Environ.* 132, 26–33.

Martinele, I., Santos, G.R.A., Matos, D.S., Batista, A.M.V., D'Agosto, M. (2010): Diet Botanical Composition and Rumen Protozoa of Sheep in Brazilian Semi-Arid Area. *Arch. Zootec.* 59, 169–175.

McDonald, M.J., Rice, D.P., Desai, M.M. (2016): Sex Speeds Adaptation by Altering the Dynamics of Molecular Evolution. *Nature* 531, 233–236.

McKissock, I., Gilkes, R.J., Walker, E.L. (2002): The Reduction of Water Repellency by Added Clay Is Influenced by Clay and Soil Properties. *Appl. Clay Sci.* 20, 225–241.

McLaren, K.P., McDonald, M.A. (2003): The Effects of Moisture and Shade on Seed Germination and Seedling Survival in a Tropical Dry Forest in Jamaica. *For. Ecol. Manag.* 183, 61–75.

Melo, A.P.C. de, Seleguini, A., Castro, M.N., Meira, F. de A., Gonzaga, J.M. da S., Haga, K.I. (2012): Superação de Dormência de Sementes e Crescimento Inicial de Plântulas de Umbuzeiro. *Semina Ciênc. Agrár.* 33, 1343–1350.

Melo, A.S. de, Gois, M.P.P., Brito, M.E.B., Viégas, P.R.A., Araújo, F.P. de, Mélo, D.L.M.F. de, Mendonça, M. da C. (2005): "Umbuzeiro" Rootstocks Development as a Answer for Fertilization with Nitrogen and Phosphorous. *Ciênc. Rural* 35, 324–331.

Melo, N., Fári, M., Teixeira, J. (1997): In Vitro Cultivation of Nodal Segments of the Umbu Tree [*Spondias tuberosa* (Arr.)Cam], in: Acta Horticulturae. International Society for Horticultural Science (ISHS), Leuven, Belgium, pp. 535–538.

Mendes, B.V. (1990): Umbuzeiro (*Spondias tuberosa* Arr. Cam.): importante fruteira do semi-arido. *Esc. Super. Agric. Mossoro* 564, 67.

Mendiburu, F. de (2014): Agricolae: Statistical Procedures for Agricultural Research.

Menezes, R.S.C., Sampaio, E., Giongo, V., Pérez-Marin, A.M. (2012): Biogeochemical Cycling in Terrestrial Ecosystems of the Caatinga Biome. *Braz. J. Biol.* 72, 643–653.

Mertens, J., Almeida-Cortez, J.S., Germer, J., Sauerborn, J. (2015): Umbuzeiro (*Spondias tuberosa*): A Systematic Review. *Rev. Bras. Ciênc. Ambient.* 36, 179–197.

Mertens, J., Germer, J., de Araújo Filho, J.C., Sauerborn, J. (2017): Effect of Biochar, Clay Substrate and Manure Application on Water Availability and Tree-Seedling Performance in a Sandy Soil. *Arch. Agron. Soil Sci.* 63, 969–983.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V., Gordon, J.E. (2006): A Global Overview of the Conservation Status of Tropical Dry Forests. *J. Biogeogr.* 33, 491–505.

Miller, A., Schaal, B. (2005): Domestication of a Mesoamerican Cultivated Fruit Tree, *Spondias purpurea*. *Proc. Natl. Acad. Sci. U. S. A.* 102, 12801–12806.

Ministério do Meio Ambiente (2005): Programa de Ação Nacional de Combate à Desertificação e Mitigação dos Efeitos da Seca.

Mogni, V.Y., Oakley, L.J., Prado, D.E. (2015): The Distribution of Woody Legumes in Neotropical Dry Forests: The Pleistocene Arc Theory 20 Years On. *Edinb. J. Bot.* 72, 35–60.

Mojid, M.A., Wyseure, G.C.L., Mustafa, S.M.T. (2012): Water Use Efficiency and Productivity of Wheat as a Function of Clay Amendment. *Environ. Control Biol.* 50, 347–362.

Monteiro, A.A. (2007): Patrimônio Cultural, Luta e Identidade. Os Indígenas Pankararu em São Paulo., in: Lima Filho, M.F., Eckert, C., Beltrão, J.F. (eds.): Antropologia e patrimônio cultural: diálogos e desafios contemporâneos. Nova Letra, Blumenau, pp. 157–174.

Moraes, M.O., Fonteles, M.C., Moraes, M.E.A., Machado, M.I.L., Matos, F.J.A. (1997): Screening for Anticancer Activity of Plants from the Northeast of Brazil. *Fitoterapia* 68, 235–239.

Moser, M. (2013): Ameaçado de Extinção, Umbuzeiro Depende de Investimento e Pesquisa [WWW Document]. URL http://www.dw.de/amea%C3%A7ado-de-extin%C3%A7%C3%A3o-umbuzeiro-depende-de-investimento-e-pesquisa/a-16772088 (accessed 4.28.17).

Moura, F. de B.P., Mendes Malhado, A.C., Ladle, R.J. (2013): Nursing the Caatinga Back to Health. *J. Arid Environ.* 90, 67–68.

Murashige, T., Skoog, F. (1962): A Revised Medium for Rapid Growth and Bio Assays with Tobacco Tissue Cultures. *Physiol. Plant.* 15, 473–497.

Murphy, P.G., Lugo, A.E. (1986): Ecology of Tropical Dry Forest. *Annu. Rev. Ecol. Syst.* 17, 67–88.

Nadia, T. d. L., Machado, I.C., Lopes, A.V. (2007): Pollination of *Spondias tuberosa* Arruda (Anacardiaceae) and Analysis of Pollinators Share with *Ziziphus joazeiro* Mart. (Rhamnaceae), Fruit Species Endemic to the “Caatinga.” *Braz. J. Bot.* 30, 89–100.

Narain, N., Bora, P.S., Holschuh, H.J., Vasconcelos, M.A. da S. (1992): Variation in Physical and Chemical Composition During Maturation of Umbu (*Spondias tuberosa*) Fruits. *Food Chem.* 44, 255–259.

Nascimento, C.E. de S., Oliveira, V.R. de, Santos, C.A.F., Drumond, M.A. (2012): Caracterização de Acessos do Banco de Germoplasma de Umbuzeiro (*Spondias tuberosa* Arruda) - BGU da Embrapa Semiárido, Petrolina, PE., in: Conference proceedings Congresso Brasileiro de Recursos Genéticos 2. Presented at the Congresso Brasileiro de Recursos Genéticos, Sociedade Brasileira de Recursos Genéticos, Belém, PA, p. 4.

Nascimento, C.E. de S., Oliveira, V.D., Nunes, R.D., Albuquerqe, T.D. (1993): Propagação Vegetativa do Umbuzeiro., in: Congresso Florestal Panamericano. Presented at the Congresso Florestal Brasileiro 7, Sociedade Brasileira da Silvicultura; Sociedade Brasileira de Engenheiros Florestais, Curitiba, PR, pp. 454–456.

Nascimento, C.E. de S., Santos, C.A.F., Oliveira, V.R. de, Drumond, M.A. (2002): Banco de Germoplasma do Umbuzeiro: Novos Acessos e Avaliações Preliminares aos Oito Anos de Idade., in: Conference proceedings Congresso Brasileiro de Fruticultura 17. Presented at the Congresso Brasileiro de Fruticultura, SBF, Belém,PA, p. 5.

Nascimento, C.E. de S., Tabarelli, M., Silva, C.A.D. da, Leal, I.R., Souza Tavares, W., Serrão, J.E., Zanuncio, J.C. (2014): The Introduced Tree *Prosopis juliflora* is a Serious Threat to Native Species of the Brazilian Caatinga Vegetation. *Sci. Total Environ.* 481, 108–113.

Neto, E.M. de F.L., Almeida, A.L., Peroni, N., Castro, C.C., Albuquerque, U.P. (2013): Phenology of *Spondias tuberosa* Arruda (Anacardiaceae) Under Different Landscape Management Regimes and a Proposal for a Rapid Phenological Diagnosis Using Local Knowledge. *J. Ethnobiol. Ethnomedicine* 9, 10.

Neto, E.M. de F.L., Peroni, N., Albuquerque, U.P. de (2010): Traditional Knowledge and Management of Umbu (*Spondias tuberosa*, Anacardiaceae): An Endemic Species from the Semi–Arid Region of Northeastern Brazil. *Econ. Bot.* 64, 11–21.

Neto, E.M. de F.L., Peroni, N., Maranhão, C.M.C., Maciel, M.I.S., Albuquerque, U.P. de (2012): Analysis of Umbu (*Spondias tuberosa* Arruda (Anacardiaceae)) in Different Landscape Management Regimes: A Process of Incipient Domestication? *Environ. Monit. Assess.* 184, 4489–4499.

Neto, J.F.B., Lacerda, J., Pereira, W.E., Albuquerqe, R., Costa, A., Santos, D. (2009): Emergência de Plântulas e Características Morfológicas de Sementes e Plantas de Umbuzeiro. *Eng. Ambient.* 6, 224–230.

Neves, O.S.C., Carvalho, J.G. de (2005): Tecnologia da Produção do Umbuzeiro (*Spondias tuberosa* Arr. Cam.). Universidade Federal de Lavras, Lavras.

Neves, O.S.C., Carvalho, J.G. de, Ferreira, E.V. de O., Assis, R.P. de (2008a): Nutrição Mineral, Crescimento e Níveis Críticos Foliares de Cálcio e Magnésio, em Mudas de Umbuzeiro, em Função da Calagem. *Rev. Ceres* 55, 575–583.

Neves, O.S.C., Carvalho, J.G. de, Ferreira, E.V. de O., Pereira, N.V. (2007a): Crescimento, Nutrição Mineral e Nível Crítico Foliar de K em Mudas de Umbuzeiro, em Função da Adubação Potássica. *Ciênc. E Agrotecnologia* 31, 636–642.

Neves, O.S.C., Carvalho, J.G. de, Ferreira, E.V.O., Pereira, N.V., Neves, V.B.F. (2007b): Efeito da Adubação Nitrogenada Sobre o Crescimento e Acúmulo de Nutrientes em Mudas de Umbuzeiro. *Rev. Bras. Ciênc. Agrár.* 2, 200–207.

Neves, O.S.C., Carvalho, J.G. de, Oliveira, E.V. de, Neves, V.B.F. (2008b): Crescimento, Nutrição Mineral e Nível Crítico Foliar de P em Mudas de Umbuzeiro, em Função da Adubação Fosfatada. *Rev. Bras. Frutic.* 30, 801–805.

Neves, O.S.C., Carvalho, J.G. de, Rodrigues, C.R. (2004a): Crescimento e Nutrição Mineral de Mudas de Umbuzeiro (*Spondias tuberosa* Arr. Cam.) Submetidas a Níveis de Salinidade em Solução Nutritiva. *Ciênc. E Agrotecnologia* 28, 997–1006.

Neves, O.S.C., Sá, J.R. de, Carvalho, J.G. de (2004b): Crescimento e Sintomas Visuais de Deficências de Micronutrientes em Umbuzeiro. *Rev. Bras. Frutic.* 26, 306–309.

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., Børresen, T. (2016): In Situ Effects of Biochar on Aggregation, Water Retention and Porosity in Light-Textured Tropical Soils. *Soil Tillage Res.* 155, 35–44.

Oddou-Muratorio, S., Davi, H. (2014): Simulating Local Adaptation to Climate of Forest Trees with a Physio-Demo-Genetics Model. *Evol. Appl.* 7, 453–467.

Oliveira, G. de, Araújo, M.B., Rangel, T.F., Alagador, D., Diniz-Filho, J.A.F. (2012): Conserving the Brazilian Semiarid (Caatinga) Biome Under Climate Change. *Biodivers. Conserv.* 21, 2913–2926.

Oliveira, P.E. de, Barreto, A.M.F., Suguio, K. (1999): Late Pleistocene/Holocene Climatic and Vegetational History of the Brazilian Caatinga: The Fossil Dunes of the Middle são Francisco River. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 152, 319–337.

Oliveira, V.R. de, Resende, M.D.V. de, Nascimento, C.E. de S., Drumond, M.A., Santos, C.A.F. (2004): Genetic Variability of Provenances and Progenies of Umbu Tree by Mixed Linear Model Methodology (REML/BLUP). *Rev. Bras. Frutic.* 26, 53–56.

Oliveira, J.A., Goncalves, P.R., Bonvicino, C.R. (2003): Mamíferos da Caatinga, in: Leal, I.R., Tabarelli, M., Silva, J.M.C. (eds.): Ecologia E Conservação Da Caatinga. Editora Universitária, Universidade Federal de Pernambuco, Recife, pp. 275–333.

Oyama, M.D., Nobre, C.A. (2004): Climatic Consequences of a Large-Scale Desertification in Northeast Brazil: A GCM Simulation Study. *J. Clim.* 17, 3203–3213.

Pare, S., Savadogo, P., Tigabu, M., Oden, P.C., Ouadba, J.M. (2009): Regeneration and Spatial Distribution of Seedling Populations in Sudanian Dry Forests in Relation to Conservation Status and Human Pressure. *Trop. Ecol.* 50, 339–353.

Pasiecznik, N.M., Felker, P., Harris, P.J.C., Harsh, L.N., Cruz, G., Tewari, J.C., Codoret, K., Maldonado, L.J. (2001): The *Prosopis julifora-Prosopis pallida* complex: a monograph. HDRA, Coventry.

Pedrosa, A., Lederman, I.E., Bezerra, J., Dantas, A., Gonzaga Neto, L. (1991): Métodos de Enxertia do Umbuzeiro (*Spondias tuberosa*Arr. Cam) em Viveiro. *Rev. Bras. Frutic.* 13, 59–62.

Pegado, C.M.A., Andrade, L.A. de, Félix, L.P., Pereira, I.M. (2006): Efeitos da Invasão Biológica de Algaroba: *Prosopis juliflora* (Sw.) DC. Sobre a Composição e a Estrutura do Estrato Arbustivo-Arbóreo da Caatinga no Município de Monteiro, PB, Brasil. *Acta Bot. Bras.* 20, 887–898.

Persson, H. (1978): Root Dynamics in a Young Scots Pine Stand in Central Sweden. *Oikos* 30, 508–519.

Pessoa, C., Costa-Lotufo, L.V., Leyva, A., de Moraes, M.E.A., de Moraes, M.O. (2006): Anticancer Potential of Northeast Brazilian Plants, in: Mahmud T.H. Khan and Arjumand Ather (ed.): Advances in Phytomedicine. Elsevier, pp. 197–211.

Pierret, A., Gonkhamdee, S., Jourdan, C., Maeght, J.-L. (2013): IJ_Rhizo: An Open-Source Software to Measure Scanned Images of Root Samples. *Plant Soil* 373, 531–539.

Polverigiani, S., McCormack, M.L., Mueller, C.W., Eissenstat, D.M. (2011): Growth and Physiology of Olive Pioneer and Fibrous Roots Exposed to Soil Moisture Deficits. *Tree Physiol.* 31, 1228–1237.

Prado, D.E. (2003): As Caatingas da América do Sul, in: Leal, I.R., Tabarelli, M., Silva, J.M.C. (eds.): Ecologia E Conservação Da Caatinga. Editora Universitária, Universidade Federal de Pernambuco, Recife, pp. 3–74.

Prado, D.E., Gibbs, P.E. (1993): Patterns of Species Distributions in the Dry Seasonal Forests of South America. *Ann. Mo. Bot. Gard.* 80, 902–927.

Projeto de Lei No 3.548, DE 2004 - Dispõe sobre a proibição da derrubada do umbuzeiro em todo país, e dá outras providências. (2004).

Queiroz, L.P. de (2006): The Brazilian Caatinga: Phytogeographical Patterns Inferred from Distribution Data of the Leguminosae, in: Pennington, R.T., Lewis, G.P., Ratter, J.A. (eds.): Neotropical Savannas and Seasonally Dry Forests: Diversity, Biogeography, and Conservation. Taylor & Francis, Boca Raton, pp. 121–157.

R Core Team (2016): R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ræbild, A., Hansen, H.H., Dartell, J., Ky, J.-M.K., Sanou, L. (2007): Ethnicity, Land Use and Woody Vegetation: A Case Study from South-Western Burkina Faso. *Agrofor. Syst.* 70, 157–167.

Ramos, M.A., Albuquerque, U.P. de (2012): The Domestic Use of Firewood in Rural Communities of the Caatinga: How Seasonality Interferes with Patterns of Firewood Collection. *Biomass Bioenergy* 39, 147–158.

Ramos, M.A., Medeiros, P.M. de, Almeida, A.L.S. de, Feliciano, A.L.P., Albuquerque, U.P. de (2008): Use and Knowledge of Fuelwood in an Area of Caatinga Vegetation in NE Brazil. *Biomass Bioenergy* 32, 510–517.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H. (2003): Effect of Soil Organic Carbon on Soil Water Retention. *Geoderma* 116, 61–76.

Reich, P.B. (2014): The World-Wide “Fast–Slow” Plant Economics Spectrum: A Traits Manifesto. *J. Ecol.* 102, 275–301.

Reis, R.V. dos, Fonseca, N., Ledo, C.A.S., Gonçalves, L.S.A., Partelli, F.L., Silva, M.G.M., Santos, E.A. (2010): Estádios de Desenvolvimento de Mudas de Umbuzeiros Propagadas por Enxertia. *Cienc. Rural* 40, 787–792.

Resende, G.M. de, Cavalcanti, N. de B., Drumond, M.A. (2004): Consumo de Frutos do Imbuzeiro (*Spondias tuberosa* Arruda) Pelos Caprinos na Caatinga. *Agrossilvicultura* 1, 203–210.

Rey, A., Petsikos, C., Jarvis, P.G., Grace, J. (2005): Effect of Temperature and Moisture on Rates of Carbon Mineralization in a Mediterranean Oak Forest Soil Under Controlled and Field Conditions. *Eur. J. Soil Sci.* 56, 589–599.

Ribeiro, E.M.S., Arroyo-Rodríguez, V., Santos, B.A., Tabarelli, M., Leal, I.R. (2015): Chronic Anthropogenic Disturbance Drives the Biological Impoverishment of the Brazilian Caatinga Vegetation. *J. Appl. Ecol.* 52, 611–620.

Ribero Filho, M., Zimmermann, M.P., Belchior, M., Raupp, M.A., Teixeira, I.M.V., Vargas, G.J.S., Ribeiro, A., Adams, L.I.L. (2012): Lei Nº 12.651, de 25 de Maio 2012.

Rodrigues, A.S.L., Pilgrim, J.D., Lamoreux, J.F., Hoffmann, M., Brooks, T.M. (2006): The Value of the IUCN Red List for Conservation. *Trends Ecol. Evol.* 21, 71–76.

Rouquerol, J., Avnir, D., Fairbridge, C.W., Everett, D.H., Haynes, J.M., Pernicone, N., Ramsay, J.D.F., Sing, K.S.W., Unger, K.K. (1994): Recommendations for the Characterization of Porous Solids (Technical Report). *Pure Appl. Chem.* 66, 1739–1758.

RStudio Team (2016): RStudio: Integrated Development for R. RStudio, Inc., Boston, MA.

Ruiz, H.A., Ferreira, G.B., Pereira, J.B.M. (2003): Field Capacity of Oxisols and Quartzipsamments Calculated from Moisture Equivalent Determination. *Rev. Bras. Ciênc. Solo* 27, 389–393.

Sá e Silva, I.M.M., Marangon, L.C., Hanazaki, N., Albuquerque, U.P. (2009): Use and Knowledge of Fuelwood in Three Rural Caatinga (Dryland) Communities in Ne Brazil. *Environ. Dev. Sustain.* 11, 833–851.

Sá, I.B., Cunha, T.J.F., Teixeira, A.H. d. C., Angelotti, F., Drumond, M.A. (2010): Desertificação no Semiárido Brasileiro, in: Conference Proceedings Conference on Climate, Sustainability and Sustainable Development in Semiarid Regions. Presented at the 2a Conferência Internacional: Clima, Sustentabilidade e Desenvolvimento em Regiões Semiáridas, ICID+18, Fortaleza, CE, pp. 16–20.

Sacramento, J.A.A.S. do, Araújo, A.C. de M., Escobar, M.E.O., Xavier, F.A. da S., Cavalcante, A.C.R., Oliveira, T.S. de (2013): Soil Carbon and Nitrogen Stocks in Traditional Agricultural and Agroforestry Systems in the Semiarid Region of Brazil. *Rev. Bras. Ciênc. Solo* 37, 784–795.

Salazar, L.F., Nobre, C.A., Oyama, M.D. (2007): Climate Change Consequences on the Biome Distribution in Tropical South America: Climate Change and Biome Distribution. *Geophys. Res. Lett.* 34.

Salcedo, I.H., Menezes, R.S.C. (2009): Agroecosystem Functioning and Management in Semi-Arid Northeastern Brazil, in: Tiessen, H., Stewart, J.W.B. (eds.): Applying Ecological Knowledge to Landuse Decisions. Inter-American Institute for Global Change Research - IICA-IAI-Scope, Paris, pp. 73–81.

Sampaio, E.V.S.B. (1995): Overview of the Brazilian Caatinga, in: Bullock, S.H., Mooney, H.A., Medina, E. (eds.): Seasonally Dry Tropical Forests. Cambridge University Press, Cambridge, pp. 35–63.

Sampaio, E.V.S.B., Silva, G.C. (2005): Biomass Equations for Brazilian Semiarid Caatinga Plants. *Acta Bot. Bras.* 19, 935–943.

Sánchez-Azofeifa, G.A., Quesada, M., Rodríguez, J.P., Nassar, J.M., Stoner, K.E., Castillo, A., Garvin, T., Zent, E.L., Calvo-Alvarado, J.C., Kalacska, M.E.R., Fajardo, L., Gamon, J.A., Cuevas-Reyes, P. (2005): Research Priorities for Neotropical Dry Forests. *Biotropica* 37, 477–485.

Santiago, L.S., Wright, S.J., Harms, K.E., Yavitt, J.B., Korine, C., Garcia, M.N., Turner, B.L. (2012): Tropical Tree Seedling Growth Responses to Nitrogen, Phosphorus and Potassium Addition. *J. Ecol.* 100, 309–316.

Santo, F. da S. do E., Maciel, J.R., Filho, S., De, J.A. (2012): Impact of Herbivory by Goats on Natural Populations of *Bromelia laciniosa* Mart. ex Schult. f. (Bromeliaceae). *Rev. Árvore* 36, 143–149.

Santos, C.A.F. (1997): Dispersão da Variabilidade Fenotípica doUmbuzeiro no Semi-Árido Brasileiro. *Pesqui. Agropecuária Bras.* 32, 923–930.

Santos, C.A.F. (1999): In Situ Evaluation of Fruit yield and Estimation of Repeatability Coefficient for Major Fruit Traits of Umbu Tree [*Spondias tuberosa* (Anacardiaceae)] in the Semi-Arid Region of Brazil. *Genet. Resour. Crop Evol.* 46, 455–460.

Santos, C.A.F., Gama, R.N.C. de S. (2013): An AFLP Estimation of the Outcrossing Rate of *Spondias tuberosa* (Anacardiaceae), an Endemic Species to the Brazilian Semiarid Region. *Rev. Biol. Trop.* 61, 577–582.

Santos, C.A.F., Nascimento, C.E. de S. (1998): Relação Entre Caracteres Quantitativos do Umbuzeiro (*Spondias tuberosa* A. Camara). *Pesqui. Agropecu. Bras.* 33, 449–456.

Santos, C.A.F., Oliveira, V.R. de (2008): Genetic Inter-Relantionships Among Species of Genus Spondias Based on AFLP Markers. *Rev. Bras. Frutic.* 30, 731–735.

Santos, C.A.F., Oliveira, V.R. de, Rodrigues, M.A., Ribeiro, H.L.C. (2011): Estimativas de Polinização Cruzada em População de *Spondias tuberosa* Arruda (Anacardiaceae) Usando Marcador AFLP. *Rev. Árvore* 35, 691–697.

Santos, C.A.F., Rodrigues, M.A., Zucchi, M.I. (2008): Genetic Variability of Umbu Trees in Brazilian Semi-Arid Region, Based on AFLP Markers. *Pesqui. Agropecu. Bras.* 43, 1037–1043.

Santos, J.C., Almeida-Cortez, J.S., Fernandes, G.W., Tabarelli, M. (2011): Caatinga: The Scientific Negligence Experienced by a Dry Tropical Forest. *Trop. Conserv. Sci.* 4, 276–286.

Santos, M.G., Oliveira, M.T., Figueiredo, K.V., Falcão, H.M., Arruda, E.C.P., Almeida-Cortez, J., Sampaio, E.V.S.B., Ometto, J.P.H.B., Menezes, R.S.C., Oliveira, A.F.M., Pompelli, M.F., Antonino, A.C.D. (2014): Caatinga, the Brazilian Dry Tropical Forest: Can It Tolerate Climate Changes? *Theor. Exp. Plant Physiol.* 26, 83–99.

Sayer, E.J., Wright, S.J., Tanner, E.V.J., Yavitt, J.B., Harms, K.E., Powers, J.S., Kaspari, M., Garcia, M.N., Turner, B.L. (2012): Variable Responses of Lowland Tropical Forest Nutrient Status to Fertilization and Litter Manipulation. *Ecosystems* 15, 387–400.

Schenk, H.J., Jackson, R.B. (2002): Rooting Depths, Lateral Root Spreads and Below-Ground/Above-Ground Allometries of Plants in Water-Limited Ecosystems. *J. Ecol.* 90, 480–494.

Schulz, K., Voigt, K., Beusch, C., Almeida-Cortez, J.S., Kowarik, I., Walz, A., Cierjacks, A. (2016): Grazing Deteriorates the Soil Carbon Stocks of Caatinga Forest Ecosystems in Brazil. *For. Ecol. Manag.* 367, 62–70.

Schumann, K., Wittig, R., Thiombiano, A., Becker, U., Hahn, K. (2011): Impact of Land-Use Type and Harvesting on Population Structure of a Non-Timber Forest Product-Providing Tree in a Semi-Arid Savanna, West Africa. *Biol. Conserv.* 144, 2369–2376.

Schuurman, J.J., Goedewaagen, M.A.J. (1971): Methods for the Examination of Root Systems and Roots, 2d ed. rev. ed. Centre for Agricultural Pub. and Documentation, Wageningen.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H. (2008): Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* 319, 1238–1240.

Seemann, J.R., Critchley, C. (1985): Effects of Salt Stress on the Growth, Ion Content, Stomatal Behaviour and Photosynthetic Capacity of a Salt-Sensitive Species, *Phaseolus vulgaris* L. *Planta* 164, 151–162.

Sharma, K.L., Mandal, U.K., Srinivas, K., Vittal, K.P.R., Mandal, B., Grace, J.K., Ramesh, V. (2005): Long-Term Soil Management Effects on Crop Yields and Soil Quality in a Dryland Alfisol. *Soil Tillage Res.* 83, 246–259.

Sietz, D., Lüdeke, M.K.B., Walther, C. (2011): Categorisation of Typical Vulnerability Patterns in Global Drylands. *Glob. Environ. Change* 21, 431–440.

Sietz, D., Untied, B., Walkenhorst, O., Lüdeke, M.K.B., Mertins, G., Petschel-Held, G., Schellnhuber, H.J. (2006): Smallholder Agriculture in Northeast Brazil: Assessing Heterogeneous Human-Environmental Dynamics. *Reg. Environ. Change* 6, 132–146.

Silva, A., Morais, S.M., Marques, M.M.M., Lima, D.M., Santos, S.C.C., Almeida, R.R., Vieira, I.G.P., Guedes, M.I.F. (2011): Antiviral Activities of Extracts and Phenolic Components of Two Spondias Species Against Dengue Virus. *J. Venom. Anim. Toxins Trop. Dis.* 17, 406–413.

Silva, K.A. da, Andrade, J.R. de, Santos, J.M.F.F. dos, Lopes, C.G.R., Ferraz, E.M.N., Albuquerque, U.P. de, Araújo, E. de L. (2015): Effect of Temporal Variation in Precipitation on the Demography of Four Herbaceous Populations in a Tropical Dry Forest Area in Northeastern Brazil. *Rev. Biol. Trop. J. Trop. Biol. Conserv.* 63, 903–914.

Silva, V. d. P.R. da (2004): On Climate Variability in Northeast of Brazil. *J. Arid Environ.* 58, 575–596.

Silva, E.C. de, Nogueira, R.J.M.C., Araújo, F.P. de, Melo, N.F. de, Neto, A.D. de A. (2008): Physiological Responses to Salt Stress in Young Umbu Plants. *Environ. Exp. Bot.* 63, 147–157.

Silva, E.C. de, Nogueira, R.J.M.C., Vale, F.H.A., Araújo, F.P. de, Pimenta, M.A. (2009a): Stomatal Changes Induced by Intermittent Drought in Four Umbu Tree Genotypes. *Braz. J. Plant Physiol.* 21, 33–42.

Silva, E.C. de, Nogueira, R.J.M.C., Vale, F.H.A., Melo, N.F. de, Araújo, F.P. de (2009b): Water Relations and Organic Solutes Production in Four Umbu Tree (*Spondias tuberosa*) Genotypes Under Intermittent Drought. *Braz. J. Plant Physiol.* 21, 43–53.

Silva Junior, J.F. da, Bezerra, J.E.F., Lederman, I.E., Alves, M.A., Neto, M.L. de M. (2004): Collecting, Ex Situ Conservation and Characterization of “Cajá-Umbu” (*Spondias mombin×Spondias tuberosa*) Germplasm in Pernambuco State, Brazil. *Genet. Resour. Crop Evol.* 51, 343–349.

Silva, N.M.D.O.E., Cardoso, J.D.S., Delabie, J.H.C., Silva, J.G. (2008): Fruit Flies (Diptera: Tephritidae) Associated with Umbu (*Spondias tuberosa*) in the Semiarid Region of Bahia, Brazil. *Fla. Entomol.* 91, 709–710.

Siqueira Filho, J.A. de (2012): The Inexorable Extinction of the são Francisco River, in: Siqueira Filho, J.A. de (ed.): Flora of the Caatingas of the São Francisco River: Natural History and Conservation. Andrea Jakobsson Estúdio, Rio de Janeiro, pp. 24–65.

Sobral, M. d. C., Carvalho, R.C., Figueiredo, R. d. C. (2007): Environmental Risk Management of Multipurpose Use of Reservoirs in Semiarid Area of são Francisco River, Brazil., in: Gunkel, G., Sobral, M. d. C. (eds.): Reservoir and River Basin Management: Exchange of Experiences from Brazil, Portugal and Germany. Universitätsverlag TU Berlin, Berlin, pp. 14–26.

Soethe, N., Lehmann, J., Engels, C. (2006): The Vertical Pattern of Rooting and Nutrient Uptake at Different Altitudes of a South Ecuadorian Montane Forest. *Plant Soil* 286, 287–299.

Sohi, S., Lopez-Capel, E., Krull, E., Bol, R. (2009): Biochar, Climate Change and Soil: A Review to Guide Future Research. *CSIRO Land Water Sci. Rep.* 5, 64.

Sousa Araújo, T.A. de, Alencar, N.L., Amorim, E.L.C. de, Albuquerque, U.P. de (2008): A New Approach to Study Medicinal Plants with Tannins and Flavonoids Contents from the Local Knowledge. *J. Ethnopharmacol.* 120, 72–80.

Sousa Araújo, T.A. de, Castro, V.T.N. de A. e, Amorim, E.L.C. de, Albuquerque, U.P. de (2012): Habitat Influence on Antioxidant Activity and Tannin Concentrations of *Spondias Tuberosa*. *Pharm. Biol.* 50, 754–759.

Souza Almeida, C.C. de, Lemos Carvalho, P.C. de, Guerra, M. (2007): Karyotype Differentiation Among Spondias Species and the Putative Hybrid Umbu-Cajá (Anacardiaceae). *Bot. J. Linn. Soc.* 155, 541–547.

Souza, A.A. de, Bruno, R. de L.A., Lopes, K.P., Cardoso, G.D., Pereira, W.E., Cazé Filho, J. (2005): Semillas de *Spondias tuberosa* Oriundas de Frutos Cosechados en Cuatro Estadios de Maduración y Almacenadas. *Rev. Bras. Eng. Agríc. E Ambient.* 9, 372–378.

Stöckli, R., Vermote, E., Saleous, N., Simmon, R., Herring, D. (2005): The Blue Marble Next Generation - a True Color Earth Dataset Including Seasonal Dynamics from MODIS. NASA Earth Observatory.

Tabarelli, M., Vincent, A. (2004): Conhecimento Sobre Plantas Lenhosas da Caatinga: Lacunas Geográficas e Ecológicas, in: Silva, J.M.C., Tabarelli, M., Fonseca, M.T. da, Lins, L.V. (eds.): Biodiversidade Da Caatinga: Áreas E Ações Prioritárias Para a Conservação. Ministério do Meio Ambiente, Brasília, pp. 101–111.

Tangkoonboribun, R., Rauysoongnern, S., Rambo, P.V., Tumsan, B. (2006): Effect of Organic and Clay Material Amendment on Physical Properties of Degraded Sandy Soil for Sugarcane Production. *Sugar Tech* 8, 44–48.

Tavares, S.C.C. de H., Nascimento, A.R.P., Nascimento, C.E. de S., Karasawa, M. (1998): Evidencia de *Colletotrichum gloeosporioides* como Patogeno de Umbuzeiros (*Spondias tuberosa*) no Brasil. *Summa Phytopathol.* 24, 51–52.

The Document Foundation (2011): LibreOffice Calc.

The World Bank (1998): Recent Experience with Involuntary Resettlement - Brazil - Itaparica (No. 17544). The World Bank, Washington D.C.

Therneau, T.M. (2015): A Package for Survival Analysis in S.

Thornthwaite, C.W. (1931): The Climates of North America: According to a New Classification. *Geogr. Rev.* 21, 633.

Tiessen, H., Feller, C., Sampaio, E.V.S.B., Garin, P. (1998): Carbon Sequestration and Turnover in Semiarid Savannas and Dry Forest. *Clim. Change* 40, 105–117.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., Williams, R. (2009): Beneficial Biofuels—The Food, Energy, and Environment Trilemma. *Science* 325, 270–271.

Tolle, M.A. (2009): Mosquito-Borne Diseases. *Curr. Probl. Pediatr. Adolesc. Health Care* 39, 97–140.

Torres, R.C., Renison, D., Hensen, I., Suarez, R., Enrico, L. (2008): *Polylepis australis*' Regeneration Niche in Relation to Seed Dispersal, Site Characteristics and Livestock Density. *For. Ecol. Manag.* 254, 255–260.

Untied, B. (2005): Bewässerungslandwirtschaft als Strategie zur kleinbäuerlichen Existenzsicherung in Nordost-Brasilien? - Handlungsspielräume von Kleinbauern am Mittellauf des São Francisco. Philipps-Universität Marburg, Marburg.

Uzoma, K.C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E. (2011): Effect of Cow Manure Biochar on Maize Productivity Under Sandy Soil Condition. *Soil Use Manag.* 27, 205–212.

Valdecantos, A., Fuentes, D., Smanis, A., Llovet, J., Morcillo, L., Bautista, S. (2014): Effectiveness of Low-Cost Planting Techniques for Improving Water Availability to *Olea europaea* Seedlings in Degraded Drylands. *Restor. Ecol.* 22, 327–335.

Verheijen, F., Jeffery, S., Bastos, A.., van der elde, M., Diafas, I. (2009): Biochar Application to Soils - a Critical Scientific Review of Effects on Soil Properties, Processes and Functions. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg.

Vidigal, M.C.T.R., Minim, V.P.R., Carvalho, N.B., Milagres, M.P., Gonçalves, A.C.A. (2011): Effect of a Health Claim on Consumer Acceptance of Exotic Brazilian Fruit Juices: Açaí (*Euterpe oleracea* Mart.), Camu-Camu (*Myrciaria dubia*), Cajá (*Spondias lutea* L.) and Umbu (*Spondias tuberosa* Arruda). *Food Res. Int.* 44, 1988–1996.

Vieira, D.L.M., Scariot, A. (2006): Principles of Natural Regeneration of Tropical Dry Forests for Restoration. *Restor. Ecol.* 14, 11–20.

Vieira, R.M. da S.P., Cunha, A.P.M. do A., Alvalá, R.C. dos S., Carvalho, V.C., Ferraz Neto, S., Sestini, M.F. (2013): Land Use and Land Cover Map of a Semiarid Region of Brazil for Meteorological and Climatic Models. *Rev. Bras. Meteorol.* 28, 129–138.

Wang, M.L., Raymer, P., Chinnan, M., Pittman, R.N. (2012): Screening of the USDA Peanut Germplasm for Oil Content and Fatty Acid Composition. *Biomass Bioenergy* 39, 336–343.

Were, B.A., Onkware, A.O., Gudu, S., Welander, M., Carlsson, A.S. (2006): Seed Oil Content and Fatty Acid Composition in East African Sesame (*Sesamum indicum* L.) Accessions Evaluated Over 3 Years. *Field Crops Res.* 97, 254–260.

West, J.B., Espeleta, J.F., Donovan, L.A. (2004): Fine Root Production and Turnover Across a Complex Edaphic Gradient of a *Pinus palustris–Aristida stricta* Savanna Ecosystem. *For. Ecol. Manag.* 189, 397–406.

Wick, B., Tiessen, H. (2008): Organic Matter Turnover in Light Fraction and Whole Soil Under Silvopastoral Land Use in Semiarid Northeast Brazil. *Rangel. Ecol. Manag.* 61, 275–283.

Wickham, H. (2009): Ggplot2. Springer New York, New York, NY.

Wilcox, C.S., Ferguson, J.W., Fernandez, G.C.J., Nowak, R.S. (2004): Fine Root Growth Dynamics of Four Mojave Desert Shrubs as Related to Soil Moisture and Microsite. *J. Arid Environ.* 56, 129–148.

Wurzburger, N., Wright, S.J. (2015): Fine-Root Responses to Fertilization Reveal Multiple Nutrient Limitation in a Lowland Tropical Forest. *Ecology* 96, 2137–2146.

Yao, Y., Gao, B., Zhang, M., Inyang, M., Zimmerman, A.R. (2012): Effect of Biochar Amendment on Sorption and Leaching of Nitrate, Ammonium, and Phosphate in a Sandy Soil. *Chemosphere* 89, 1467–1471.

Yavitt, J.B., Harms, K.E., Garcia, M.N., Mirabello, M.J., Wright, S.J. (2011): Soil Fertility and Fine Root Dynamics in Response to 4 Years of Nutrient (N, P, K) Fertilization in a Lowland Tropical Moist Forest, Panama. *Austral Ecol.* 36, 433–445.

Young, D.A., Smith, D.E. (2000): Simulations of Clay Mineral Swelling and Hydration: Dependence upon Interlayer Ion Size and Charge. *J. Phys. Chem. B* 104, 9163–9170.

Zhou, Z., Shangguan, Z. (2006): Vertical Distribution of Fine Roots in Relation to Soil Factors in *Pinus tabulaeformis* Carr. Forest of the Loess Plateau of China. *Plant Soil* 291, 119–129.

9. Annex

9.1 List of Additional Publications

This section contains additional publications or conference contributions, which were developed in the context of this dissertation but not incorporate in previous chapters. Given is the title, contributing authors, place of publication, and the abstract.

Sustainable land management probabilities – Improving benefits for small-scale farmers in Brazil's semiarid Caatinga biome

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Submitted for publication to Regional Environmental Change.

Abstract

In semi-arid Northeast Brazil, the Itaparica dam construction in 1988 affected the livelihood and environment of roughly ten thousand households. After resettlement on less fertile areas around the Itaparica reservoir, almost half of the households derived income through irrigated cropping on small plots as compensation for property loss when flooding the reservoir. Yet the majority of rural dwellers in the semi-arid region have no access to enhanced irrigation infrastructure and derive their income from the native dry-forest Caatinga via livestock farming, collecting fruits, and extracting firewood. The livelihoods of farmers have been threatened by recurring droughts, inadequate land use, and severely limited access to water.

We discuss the adoption potential of sustainable land-use practices via transdisciplinary approaches. We used constellation analysis (CA) to identify elements in the current situation of land management to establish influences of innovations as nodes for a Bayesian network (BN).

Through scenario-based management options for sustainable land management, we developed probabilities of practice uptake. The target is to strengthen sustainable conservation via natural resources, while securing incomes of smallholders cultivating dryland.
In collaboration with stakeholders and experts, 25 nodes were identified to build the BN, which were tested under various scenarios. Exemplarily, using grafted seedlings reinforces the likelihood for successfully adopted project innovation by ca. 80 %. Adopting all suggested project innovations secures final objectives—ecosystem health and farmer benefits—with a probability of approximately 90 %. The analysis disentangled the relevance of each cultivation measure, which may impede farmers to adopt the innovations, such as hesitance towards the risks, necessity to cultivate seedlings, or high investments. Simulating different values allows for analyzing conditions for the intervention's adoption success and finally securing objectives. Ultimately, crucial actions such as fencing-off livestock were identified.

Keywords: Adoption rate, Bayesian network, Caatinga forest, Northeast Brazil, Sustainable land management, Transdisciplinary approach.

The contribution of innovative agricultural systems to sustainable water reservoir use in NE-Brazil

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Published in: Tropentag 2012. Resilience of agricultural systems against crises. Book of abstracts, Cuvillier Verlag, Göttingen, p.192.

Abstract

The construction of the Itaparica dam and reservoir induced changes concerning the agricultural production systems in the micro-region Itaparica, Sao Francisco river basin. Traditional systems – mainly a combination of dryland farming in the river flood plains and livestock farming in the adjacent dryer areas – were replaced by irrigation agriculture. Even though wide areas with irrigation infrastructure were established the sandy soils of many areas are not suitable for irrigation farming. Lack of adequate arable land causes a shortage of income opportunities for

local farmers. Thus large share of many household incomes is derived by compensatory payments from the dam operator. Persistent problems are inappropriate farming practices in irrigation, inaccurate use of agrochemicals and overstocking of livestock. As a consequence soil salinization, overgrazing, erosion, and contamination and eutrophication of the reservoir increase and threaten local peoples' livelihoods. The joint research project INNOVATE aims at innovative coupling nutrient cycles to counteract erosion, soil degradation, and emission of greenhouse gases. The agriculture-related sub-projects "Terrestrial Production" and "Economy" will do research with the implementation of a sustainable and productive agriculture with closed nutrient cycles. This can contribute to reduce the above mentioned negative impacts, ensure food supply, and additionally provide an important income source for the local population. Biochar, lake sediments, and manure combined with micro-catchments and multipurpose leguminous perennial food crops and feeds, shall improve soil quality and water storage capacity. The combination of local and fast-growing trees to the crop areas meets the needs for firewood and forage for the dry season and reduces the pressure on natural vegetation, conserving its biodiversity. The results will be assimilated in a model system quantifying soil organic matter dynamics. Economic analyses on farm level monitor the profitability of these systems and facilitate recommendations for extension service and policy makers to sustainable establish them. Field trials for soil amendment and micro-catchment will be installed on dryer areas next to the main irrigation areas, while surveys and measurements on livestock systems and socio-economic data will be assessed on farm level by structured questionnaires, participatory methods, and structured observations and measurements.

Keywords: Agriculture, soil amendment, micro-catchment, reservoir.

Soil Amendment Impact on Root and Root-Tuber Development of Umbu Trees

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Published in: Tropentag 2015. Management of land use systems for enhanced food security – conflicts, controversies and resolutions. Book of abstracts, Cuvillier Verlag, Göttingen, p.149

Abstract

The Caatinga in northeastern Brazil is a semiarid ecosystem that comprises with 850,000 km^2 almost 10 % of the Brazilian territory. With 20 million inhabitants it is the most densely populated semiarid region of the world. It is a highly endangered ecosystem mainly through deforestation, fires, and pasture establishment. The umbu tree (*Spondias tuberosa* Arr.) is one of the native Caatinga trees that can survive the high temporal and spatial variability of water supply. The umbu fruit is an important nutrition source for humans and the wild life in the Caatinga. Humans use the Umbu fruit to produce juice, sweets, licorices, and others. The high pressure on this ecosystem by humans together with water scarcity, however, impede the emergence of new young trees. Therefore this study investigates how different soil amendments as biochar, goat manure, and mineral fertilizer added to planting holes can influence the rooting system of young umbu trees to potentially increase water uptake during infrequent and small rainfall events. This includes the development of root tubers which are essential for the survival of the tree during dry seasons, since they are able to store water, minerals, and organic solutes. The qualitative description of the root-system of three year old seedlings of *S. tuberosa* will include the vertical and horizontal extent of primary and secondary roots, as well as the number and size of root-tubers. To harvest the root-tubers the entire rootstock was manual excavated and the root-tubers are collected and the total number, fresh weight, and size of tubers are recorded. Root length density of fine roots and fine root biomass within the planting hole are

measured in manual washed samples out of a volumetric soil sample taken in two different depths (0 – 300 mm and 300 – 600 mm). Finally the comparison of root systems with above-ground biomass might help to understand underlying processes that favor young umbu tree survival.

Keywords: Biochar, root length density, soil amendment, umbu.

Using Bayesian Networks to Depict Favoring Frame Conditions for Sustainable Land Management: Umbuzeiro-Tree Planting by Smallholders in Brazil

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Published in: Tropentag 2015. Management of land use systems for enhanced food security – conflicts, controversies and resolutions. Book of abstracts, Cuvillier Verlag, Göttingen, p.405

Abstract

Dam construction in 1988 changed the economic basis of ten-thousand farming families who resettled involuntarily on the less fertile areas around Itaparica reservoir, semi-arid Northeast Brazil. A few now derive income through irrigated cropping on rather small plots, whereas, the majority of rural dwellers has no access to improved irrigation infrastructure as a compensation for flooding the area. These smallholdings rely on small-scale livestock farming, and collecting fruits and firewood from the Caatinga vegetation (native dry forest). The farmers' livelihoods are however threatened by recurring droughts, in sustainable land-use practices and the difficult access to water. In this context, the ‘Umbuzeiro-tree planting experiment' tests the endemic, drought-resistant species *Spondias tuberosa* Arruda, applying different soil amendments. The tree is deemed sacred by indigenous tribes and generally considered multipurpose with several benefits for both ecosystem and people. The purpose of the study is exemplarily estimating the adoption potential of innovations for a sustainable land management, in this case planting the Umbuzeiro-tree. We used constellation analysis to identify elements of the current situation and developed a Bayesian Network (BN) to estimate probabilities of practice uptake. Two representative groups of farmers, an organization supporting the farmers, a plant cultivation company, and three plant and soil experts took part in the study as main stakeholders. The BN focuses on the sustainable conservation and use of the natural environment (environmental health), and securing incomes of smallholders cultivating dryland crop areas (‘sequeiro'). The objectives are mathematically improved or not by 25 interacting nodes under different scenarios. Enabling, disabling or setting factors at different values allows analyzing different frame conditions to identify crucial elements for the intervention's future success and positive impact on objectives. Exemplarily, incentives and supply of externally grown, grafted *S. tuberosa* seedlings reinforce likelihood for project innovations being adopted by 41 %. Ultimately, pushing chances for improved farmer incomes while benefiting ecosystem health with long-term character to 91,5 %, *vice versa*, the analysis allows identifying conditions, which may impede farmers to adopt the innovations.

Keywords: Adoption potential, Bayesian networks, Caatinga, native species, Northeast Brazil, smallholdings, sustainable land management.

Income Alternatives of Smallholders at the Itaparica Reservoir in NE-Brazil

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Published in: Tropentag 2015. Management of land use systems for enhanced food security – conflicts, controversies and resolutions. Book of abstracts, Cuvillier Verlag, Göttingen, p.511.

Abstract

Irrigation farming is seen as a suitable tool to promote rural development in the semiarid Northeast region of Brazil. Especially in the last two decades, federal and state-owned authorities established several irrigation projects along the lower-middle São Francisco River to provide local smallholders the opportunity to generate income and consequently, reduce rural exodus. Due to lack of infrastructure and scarcity of irrigable areas, income derived from agricultural activities is, in many cases, still not sufficient to provide the livelihood for smallholders. Thus, they depend on income alternatives outside irrigation farming.

This study identifies and evaluates income alternatives of smallholders in the Apolônio Sales and Icó-Mandantes irrigation projects in the municipality Petrolândia, Pernambuco. It also weighs the alternatives' importance from an economic perspective as well as by the farmers' perspective. Furthermore, potential innovative income alternatives are assessed concerning their economic viability, social acceptance, and practicability. A special interest lies upon Umbu production, the fruit of the endemic xerophytic tree *Spondias tuberosa* Arruda, on drylands to reduce the pressure on irrigated areas and contribute to a more sustainable land use. A random sample of 50 farmers were interviewed - 20 interviews were conducted in the rather prosperous community of Apolônio Sales and 30 in Icó-Mandantes. Although being planned and constructed at the same time, the communities differ in many aspects, such as farm size, farmers' networks, education, capital availability, infrastructure, and social and political influence. Additionally, ten experts were interviewed to gain an overview of the socioeconomic situation of the smallholders and to analyses other potential income sources. Although most smallholders still consider themselves as farmers and mentioned crop production as their most important income source, only two of the interviewed smallholders gain their living solely with farm income. Especially in Icó-Mandantes, most households relied strongly on non-agricultural income – mainly social benefits and off-farm work of family members. Three promising income alternatives were identified. Umbu production, beekeeping, and fishery may, despite existing limitations, have the potential to improve the middle or long term income situation of the smallholders and help to reduce the pressure on the irrigable land.

Keywords: Alternative land use, income alternatives, irrigated agriculture, Northeast Brazil

9.2 Additional material

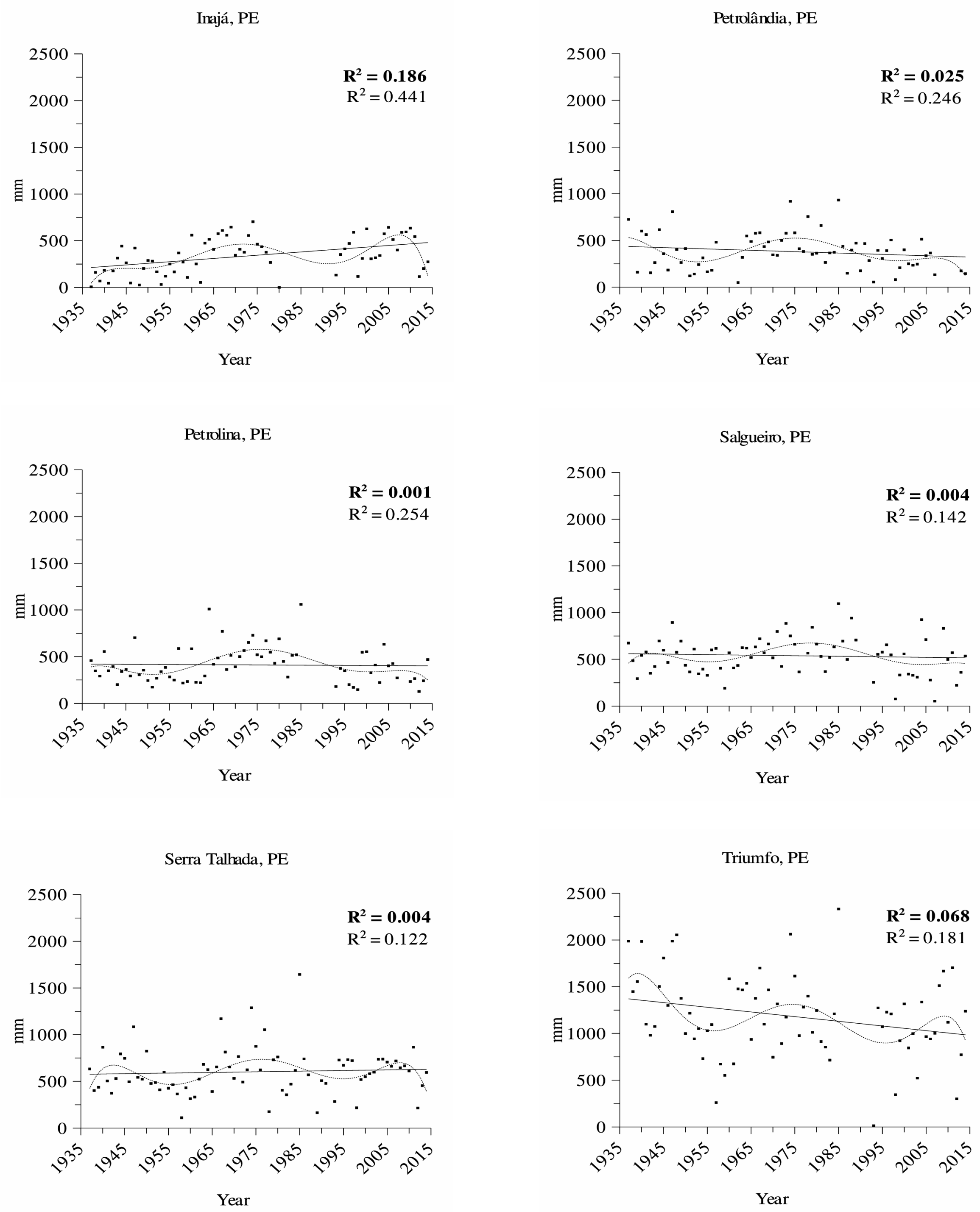

Figure 9.1: Trend in annual precipitation from 1937 until 2013 for six stations in Pernambuco, data for Petrolândia not available for all consecutive years (APAC, 2015). Continues line represents least-squares linear regression with its R^2 in bold, dashed line represents polynomial regression of 6th degree with its R^2 in regular font.

Acknowledgements

Numerous people supported me in many ways during my conferral of a doctorate. Therefore, I would like to express my gratefulness to everyone who supported me on my way to conclude this dissertation.

First of all, I would like to thank Prof. Dr. Joachim Sauerborn and Dr. Jörn Germer for accepting me as their doctoral student and providing the framework for my dissertation. This gave me the opportunity to get know the stunning Caatinga biome, as well as its emblematic sacred tree Umbuzeiro. Prof. Dr. Sauerborn and Dr. Germer together supervised my work and were always willing to provide advice, valuable help and enable stimulating discussion, regardless of the thousands of kilometers between us. I am very thankful for the precious support from Dr. Germer while setting up the field trial in Brazil, and his multiple visits in the field. Furthermore, I am grateful to Eva Schmidt for her great support with all the administrative issues, which are countless if you are 8,000 km away from the campus in Hohenheim. Thanks to Prof. Dr. Christof Engels for his kind willingness to be co-examiner of this dissertation. I also would like to thank Prof. Dr. Martin Kaupenjohann and Christine Beusch for my temporary workstation at the TU Berlin and stimulating cooperation.

I am grateful to acknowledge the financial support of my work by the German Federal Ministry of Education and Research (BMBF). For additional funding, which supported me during the critical final phase of my field work, I would like to express my gratitude to the Foundation fiat panis Ulm, Germany.

The start of my work-life in Brazil was seamless due to countless supporters. Therefore, I am very thankful for the support I received, especially during the early stage of my work, from Dr. José Coelho de Araújo Filho and Paulo Cardoso de Lima. I want to thank Dr. Geraldo Majella Bezerra Lopes as well as Maria Cristina Lemos da Silva and her team for their lab support. Thanks to Dr. Francisco Pinheiro de Araújo and Dr. Magnus Dall Igna Deon for providing essential elements for my field work. For providing the field site as well as for her hospitality I want to thank Joana Isabel Silva Nogueira. And a special thanks goes to my local handymen Antônio Marques de Sá Dantes, José Aparecido de Lima Filho and Victor Ribeiro Dantas de

Fonseca. Further I would like to thank Simon Bitterwolf for his great job during his field work on Umbuzeiro in which I was able to support him.

For the valuable and great support during the writing process of my publications, I want to thank my co-authors, which I have not mentioned yet. Thank you, Prof. Dr. Jarcilene Silva de Almeida-Cortez, Dr. Sonja Germer and Prof. Dr. José Alves de Siqueira Filho.

Affidavit

pursuant to Sec. 8(2) of the University of Hohenheim's doctoral degree regulations for Dr.sc.agr.

1. I hereby declare that I independently completed the doctoral thesis submitted on the topic

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2. I only used the sources and aids documented and only made use of permissible assistance by third parties. In particular, I properly documented any contents which I used - either by directly quoting or paraphrasing - from other works.
3. I did not accept any assistance from a commercial doctoral agency or consulting firm.
4. I am aware of the meaning of this affidavit and the criminal penalties of an incorrect or incomplete affidavit.

I hereby confirm the correctness of the above declaration. I hereby affirm in lieu of oath that I have, to the best of my knowledge, declared nothing but the truth and have not omitted any information.

Freiburg, 04.05.2017

(Place, date) (Signature)